NUTRIENT DYNAMICS AND CROP PRODUCTIVITY IN LOWLAND LATERITIC SOIL (AEU 10) UNDER RICE RESIDUE MANAGEMENT PRACTICES

by

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(2017 - 21 - 006)

THESIS

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DECLARATION

I, hereby declare that this thesis entitled **"NUTRIENT DYNAMICS AND CROP PRODUCTIVITY IN LOWLAND LATERITIC SOIL (AEU 10) UNDER RICE RESIDUE MANAGEMENT PRACTICES"** is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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Symbols / Notations and Abbreviations

AAN :	Amino acid nitrogen
AEU :	Agro ecological unit
AMN :	Ammoniacal nitrogen
ARS :	Agricultural Research Station
CD :	Critical difference
CRD :	Completely randomized design
dSm^{-1} :	Deci Siemen per meter
EC :	Electrical conductivity
FCO :	Fertilizer control order
FT-IR :	Fourier transform infrared spectroscopy
HWEC :	Hot water extractable carbon
KFRI :	Kerala Forest Research Institute
MWHC :	Maximum water holding capacity
MWD :	Mean weight diameter
MBC :	Microbial biomass carbon
PGPR :	Plant growth promoting rhizobacteria
PNP :	Para nitro phenol
POP :	Package of practices
POXC :	Permanganate oxidizable carbon
RBD :	Randomized block design
RHB :	Rice husk biochar
RSB :	Rice straw biochar
SEM :	Scanning electron microscope
SPSS :	Statistical package for social sciences
THN :	Total hydrolysable nitrogen
TPF :	Tri Phenyl Formazan
VRH :	Vermicomposted rice husk
VRS :	Vermicomposted rice straw
WASP :	Web Agri Stat Package
WSC :	Water soluble carbon

INTRODUCTION

1. INTRODUCTION

One of the most important components of sustainable agriculture is the cropping system, since it provides more efficient nutrient cycling. The fact that degradation of the world's cultivated soil is greatly responsible for the low and plateauing yields has been brought out from several studies. The soil which is amenable to loss rapidly is formed over millennia and this difference represents the greatest global threat to nutrient dynamics in agriculture. This indirectly reveals that nutrient management is essential to provide food and nutritional security to current and future generations. Maintenance of the desired ecological balance, enhancement and preservation of soil functions and protection of biodiversity above and below ground are all implied through the terms nutrient dynamics and soil sustainability. Healthy soils lead to healthy food or healthy soils constitutes the foundation of thriving ecosystems and societies and are directly connected with the food and nutritional security, water quality, human health, climate change mitigation/adaptation and biodiversity. Conservation of soil health and crop productivity is the central theme for sustainable agricultural practices. It is unrealistic to expect that the increasing crop production demands will be met by a soil ecosystem that is unhealthy and constrained. Soil fertility decline can be accessed via expert knowledge systems, the monitoring of soil chemical properties over time (chrono sequences) or at different sites (bio sequences) and through the calculation of nutrient balances, with the last one being the mostly used and cost-efficient technique. Nutrient monitoring is basically a diagnostic tool for soil productivity and sustainability assessment of the system.

Soil, is difficult to be rated in terms of the importance of different soil functions, since all of them are vital to our well-being to some extent. Healthy soils are essential for healthy plant growth and other ecosystem services. Soil health is characterized as a dynamic, life sustaining condition that supports macro and micro-organisms, nutrient cycling and physical properties needed to provide the basic necessities of life, namely, food, feed, fiber, fuel and shelter. Management practices that increase Soil organic carbon (SOC) or soil organic matter (SOM) are often highlighted, since, even a small change / improvement in that can have multiple cascading effects on soil health, and ultimately on crop productivity and profitability. Soil quality on the other hand as defined by the USDA Natural Resource Conservation Services is "the capacity of specific kind of soil to function, within natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation. Changes in the capacity of soil to function are generally reflected in soil properties that change in response to management or climate".

The soils of Kerala, a state on the south-western Malabar Coast of India, known in the earth science literature as the 'type locality' of 'laterite', a name first described by Francis Buchanan-Hamilton in 1807 at Angadipuram of Malappuram district, have been developed by the pedogenic process of laterization. This process leads to distinct variations in the soil due to the exclusive influence of climate, topography and vegetation. The tropical climate prevailing in the region, characterized by heavy rainfall and high temperature, with alternate wet and dry periods favour the process of laterization, leading to the leaching of soil, involving the net loss of silica and other soluble materials like alkali and alkaline earth cations from the system through the percolating water, oxidative loss of organic matter and accumulation of iron and aluminium on the surface (Bridges, 1977; Eswaran and Bin, 1978). In general these soils are gravelly, strongly acidic, poor in silica, dominant in kaolinitic clay, often underlain by plinthite, low to moderate in base saturation, rich in iron and aluminium oxides, high in phosphorus fixation and low in inherent fertility. The process of erosion sweeps away the topsoil along with organic matter and exposes the subsurface horizons. On an average, 15- 18 t ha^{-1} of top fertile soil is eroded in the humid tropical region of Kerala, ultimately resulting in low fertility status, low crop productivity, less ground water recharge *etc*. (Natarajan *et al*., 2005). Another important reason for degradation is the loss of organic matter by virtue of its temperature mediated rapid decomposition, contributing to the loss of rapid soil fertility in these tropical regions. Consequences of depletion of organic matter are poor soil physical health, loss of favourable biology and occurrence of multiple nutrient deficiencies. It has been reported that next to poor rain water management, depletion of nutrients caused by organic matter deficiency is an important cause of soil degradation in humid tracts (Surendran and Murugappan, 2010; Surendran *et al*., 2016).

Even though soil is not an inexhaustible storehouse of plant nutrients, farmers have been exploiting the finite reserves of nutrients in it for a long time. The incessant efforts for enhancing crop production from shrinking land resources will further magnify the depletion of these limited nutrient reserves. Continuous cropping with inorganic fertilizers alone causes decline in soil organic matter and loss of inherent soil fertility, posing serious threat to the sustainability of agro ecosystems. However, these constraints can be overcome by regular and judicious application of fertilizers along with manures and liming materials. Fruit crops, plantation crops, spices, beverages and stimulants, and vegetable crops are successfully grown in lateritic soils. It also supports growth of rice in low-lying areas.

The state of Kerala has been delineated in to five agro climatic zones using a matrix built upon altitude, rainfall, soil and topography. These agro climatic zones have been further divided into 23 agro ecological units. The agro-ecological unit AEU 10 designated as North Central Laterites is delineated to represent midland laterite terrain of Kerala. The unit encompasses 62 *panchayats*, three municipalities, and a corporation each in Thrissur and Palakkad districts and covers 4.41 per cent of geographical area of the state (KAU, 2016).

Rice is the most important food crop of the developing world, the staple food of more than half of the world's population, and an important residue producing crop in Asia. Rice (*Oryza sativa* L.) has played a crucial role in feeding a large portion of the population in the growing world, since it was domesticated 7000 years BP in Assam-Meghalaya areas of India and the mountain regions of Southeast Asia and Southwest China (Swaminathan, 1984). As per FAO statistics, during the period 1961-2018, rice area and production in different countries have increased from 115 million ha and 215 million tonnes to 167 million ha and 782 million tonnes, respectively. Rice is cultivated in 118 countries, and out of 167MT hectares of world's rice producing area, 146 million hectares are in Asia, which accounts for 91 per cent of the world rice production (FAO, 2019). India ranks second in rice production after China, covering 43.79 million ha, with a production of 112.91 million tones and productivity of 2578 kg ha^{-1} in 2018-19 (GOI, 2019). The area, production and productivity of rice in Kerala is 1.98 lakh ha, 5.78 lakh tones and 2920 kg ha^{-1}, respectively in 2018-19 (GOK, 2019).

Straw and husk are the major residues that are generated in copious amounts during rice cultivation and processing. Straw is the residual stalk left over after rice grains are removed during threshing, while rice husk is the outer layer of brown rice grain. The average ratio of rice grain: rice husk: rice straw is 1:0.25:1.25 (Haefele *et al*., 2011). Globally, 769.75 million tonnes of rice straw and 153.95 million tonnes of rice husk are produced. In India, straw and husk production are 168.50 million tonnes and 33.70 million tonnes, respectively (FAO, 2017). Rice residues are good sources of nutrients and primary source of organic matter. Straw at harvest contains 0.5-0.8 per cent N, 0.07-0.12 per cent P_2O_5, 1.16-1.66 per cent K_2O, 0.05-0.1 per cent S, and 4-7 per cent Si. This translates to about 40 per cent of the nitrogen, 30-35 per cent of the phosphorus, 80-85 per cent of the potassium, 40-45 per cent of sulphur and 80 per cent silicon taken up by the plant and which remain in the vegetative parts at maturity (Dobermann and Fairhurst, 2000). Rice straw is notable from other straws with its higher silicon and lower lignin content which designates it as a ligno-cellulosic biomass with 35-40 per cent cellulose, 25-30 per cent hemicellulose, and 10-15 per cent lignin (Thygesen *et al*., 2003). Rice husk is the by-product generated in abundance from rice milling units, containing nearly 40 per cent cellulose and 30 per cent lignin with applications in steel, cement and bricks industry. Soil fertilization is an emerging trend for rice husk utilisation.

Many a times, the crop residues are looked upon as waste materials that calls for disposal, but it has been increasingly realized that they are important organic resources and not wastes. In India, the large quantities of agricultural residues, especially rice and wheat straw are currently utilised either as raw material for paper industry or as animal feed sources. However, the collection and disposal of these residues over and above that made use of are becoming difficult and expensive. Hence, in order to clear the field rapidly and inexpensively and allow tillage practices to proceed unimpeded by residual crop material, farmers mostly opt for the quick and easy way of burning it in the fields, thereby creating significant air pollution and associated environmental problems observed in recent decades, especially in north India during Winter. Disposal of the residues in land-fills and burning are equally dangerous. Residue burning contributes towards the emission of greenhouse gases (CO_2, N_2O, CH_4), air pollutants (CO, NH_3, NO_X, SO_2, volatile organic compounds), particulate matter and smoke, thereby posing threat to human health and also contributing towards environmental changes and global warming. During burning, it generates huge quantity of smoke and greenhouse gases; the latter is affected by moisture, which enhances emission of CO, CH_4 and other organic carbons, whilst inhibiting N_2O emission (Arai *et al*., 2015). Further, the complete burning of agriculture residues produces ‘ash’, which contains very few nutrients, that also in traces. Hence, burning cannot be considered as a viable option for residue management.

Appropriate management of crop residues for agricultural use is of great significance and relevance. One of the best management options is the recycling of crop residues, which converts the surplus farm waste into useful products that meets nutrient requirement of crops. Impacts of residue management on soil organic matter and long term fertility is becoming more relevant in the context of soil quality, as evident from many of the earlier studies.

Yadvinder-Singh *et al*. (2004) noticed that incorporation of rice residues for seven years increased soil organic carbon content of the sandy loam soil significantly, in comparison with straw burning or residue removal. Recycling of crop residues is suggested as a potential means for sustaining soil fertility and productivity over the long-term (Singh and Rengel, 2007). Incorporation of crop residues will improve the soil organic matter content, nutrient availability, nutrient dynamics, and soil aggregation (Benbi *et al*., 2012). Returning the straw to the agricultural fields avoids wastage of resources and environmental pollution, increases soil organic carbon, mineral nutrient content, and improves soil structure and other soil physico-chemical properties (Cao *et al*., 2016; Yan *et al*., 2018; Bernard, 2020). Compared with long-term single application of chemical nitrogen fertilizer, straw incorporation with chemical nitrogen fertilizer was more beneficial for increasing soil NH_4^+ reserves (Wu *et al*., 2018).

Even though soil incorporation of straw is a good proposition for enhancing soil fertility, the current intensive cropping systems leave too little time for its proper decomposition and related effects. The richness in terms of lignin and cellulose in rice husk makes it difficult for its degradation under natural conditions. Despite claims that rice residues are rich in silica and potential sources of plant nutrients, they are not widely used as source of plant nutrients, mainly because of the wide C: N ratio that prolongs the decomposition, limiting its benefit to the current crop. Direct application also hinders the intercultural operations, thus necessitating an alternative waste management strategy for the disposal of rice residues.

Conservation agriculture and recommended management practices are collectively helpful to offset part of emissions due to unscientific agriculture practices. Intensive agricultural practices without caring for the environment have supposedly played a major role towards the enhancement of the greenhouse gases. As far as soil fertility restoration and climate change are concerned, it is ideal to recycle this organic waste through composting and carbonization.

Despite the fact that agricultural soils are considered as a source of greenhouse gas emissions, its potential role as a sink cannot be neglected. Every kilogram of soil organic carbon (SOC) represents 3.7 kg of CO_2 removed from the atmosphere (Mc-Conkey *et al*., 1999). Organic amendments are regarded as one of the key factors responsible for soil carbon sequestration in paddy fields over the past two decades, with several studies reporting that the effects of organic amendments on soil carbon sequestration can last for 20 to 40 years in paddy fields and projecting SOC to reach a steady state in the near future (Rui and Zhang, 2010). In India, the area under rice cultivation is mainly under the submerged system of cultivation, where organic matter preferentially accumulates, with its influence on active and passive pools of soil carbon (Rajkishore *et al.*, 2015). Slower decomposition of organic matter and higher net productivity of submerged paddy soils lead to net carbon accumulation (Sahrawat, 2005).

Composting is an excellent waste management strategy, which yields a biologically stable organic matter. Crop residues contain nutrients in their recalcitrant forms, which, on composting get transformed into humified matter through the activity of soil biota. The process of vermicomposting has emerged as an environment friendly waste management method as well as an attractive alternative to chemical fertilizers by converting organic detritus into high quality organic fertilizers. In vermicomposting, earthworms act as a voracious feeder, modifying the composition of organic waste, gradually reducing its organic carbon and C: N ratio, while retaining more nutrients (nitrogen, potassium, phosphorus, and calcium). The nutrient content is generally higher in vermicompost than traditional compost. The intestine of earthworms contains a wide range of microorganisms, enzymes and hormones, which aid in the rapid decomposition of partially digested material, transforming them into vermicompost in a short time. Worm casts/ vermicast is the organic form of fertilizer, also known as worm manure produced by earthworms. Worm cast is a resource that can be used in agriculture due to their effects on soil property enhancement and nutrient dynamics.

On the other hand, Biochar is a carbon rich material produced through thermal decomposition of organic material or biomass through a process of carbonisation, and is a novel technology for improving agricultural productivity. It is also a resource to combat climate change and global warming via sequestration of atmospheric CO_2. The most prominent benefit of biochar is its longevity, since it can remain in the soil for many years. Accordingly, biochar application helps to reduce the repeated addition of soil amendments and minimise the possibility of new contaminants reaching the soil through addition of synthetic soil amendments. Application of biochar is a good soil management practice because of its potential to improve soil fertility and soil pH, increase the cation exchange capacity, enhance soil carbon, mitigate soil green-house gas emissions, reduce leaching of nutrients and chemicals, increase fertilizer use efficiency, and enhance agriculture productivity (Cheng *et al*., 2006; Lehmann and Rondon (2006); Dainy *et al*., 2015; Rajakumar, 2019).

As per the reports of the Intergovernmental Panel on Climate Change (IPCC), the annual temperature and rainfall will vary considerably in the future. Such changes in climate will have a significant effect on the organic matter dynamics of the soils around the world. Climate and organic matter dynamics in the soils are highly correlated. Hence, suitable strategies need to be formulated for coping up with the change in organic matter dynamics in the soils for ensuring sustainability of production. Organic matter decomposition increases with higher temperature, which is considered as a critical issue for agriculture sustenance in future (Conant *et al*., 2011). The temperature sensitivity of soil organic matter decomposition has gained increasing interest because of its potential importance to soil carbon (C) cycling in response to future global warming. Soil organic matter (SOM) includes a complex continuum of organic components with varying chemical structures, and a wide range of turnover times. Relatively recalcitrant C makes up the bulk of SOM and has a longer turnover time relative to labile C. So, its response to temperature may be particularly influential on predictions of future C concentrations in soils and the atmosphere.

Mineralization of organic materials added to soil is governed by temperature, which indicates that global warming and climate change will make our soil more vulnerable in terms of carbon loss, thus reducing soil productivity. Fresh organic amendments *i.e.* farmyard manure and residues are readily utilized by microorganisms, while matured inputs (e.g., vermicompost and biochar) provide more recalcitrant polymerized compounds, which are less prone to mineralization/decomposition. The CO_2 released from soil through microbial decomposition of organic materials contributes 99 per cent of the total emission and thus reduces soil organic pool. Hossain *et al*. (2017) concluded that climate-smart soil management practices might help in reducing CO_2 emission from soil. Net reduction in CO_2 emission means increased soil carbon storage, which is commonly known as carbon sequestration in agriculture. Therefore, carbon sequestration is the prime requirement to conserve soil organic matter, not only for a source of plant nutrients, but also as a potential sink of atmospheric CO_2. A prediction on carbon mineralization of organic materials in soil is vital for foreseeing CO_2 emission. Information on carbon dioxide emission from different rice residues and their products and their temperature dependence is limited in lateritic soil.

The decline in soil fertility does not get the same public attention as that of floods, droughts, pest infestation, *etc*. because it is a gradual process and not associated with catastrophes and mass starvation, and therefore largely invisible. Hence, it is imperative to manage rice residues to derive benefits for soil health and crop productivity in the changing climate change scenario. The uniqueness in soil forming and development processes under the humid tropical climate dictates the dynamic equilibrium of different nutrient ions existing in solid and solution phase. The understanding of dominant forms or fractions of each nutrient existing in lowland lateritic soil is important in managing the fertility level of these nutrients for rice. With this background, the present investigation titled "Nutrient dynamics and crop productivity in lowland lateritic soil (AEU 10) under rice residue management practices" was undertaken with the following objectives:

- Characterization of rice residues and their products for physical and chemical properties
- To study the kinetics of carbon mineralization
- To evaluate the efficacy of rice residues and their products on lowland rice

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

A comprehensive overview of all the expertness available on previous research conducted and published related to the topic “Nutrient dynamics and crop productivity in lowland lateritic soil (AEU 10) under rice residue management practices” are organized in this chapter under different titles.

2.1. RICE RESIDUES AND ITS CHARACTERIZATION

Rice is the world’s second largest cereal crop that produces the largest amount of crop residues (Soest, 2006). Rice husk is the by-product generated in abundance from rice milling units. It is estimated that 0.20 t of husk is produced from about one tone of paddy, depending on the variety, climatic condition, and geographical location (Ampadu *et al*., 2010). Assuming a harvest index of 0.5, nearly 200 mt of rice straw is produced in India annually (Benbi and Yadav, 2015).

Rice residues are used as animal feeds or fertilizers by most of the farmers. However, these are considered as inferior to other animal feeds due to their high silica content (Mandal *et al*., 2004), which decreases its digestibility by the animals. In addition, rice residues can be used as an energy source in thermochemical conversion processes such as gasification and combustion (Yoon *et al*., 2012 and Delivand *et al*., 2011) or in bioconversion processes for production of bioethanol (Karimi *et al*., 2006) and biogas (Teghammar *et al*., 2012). The ash produced from gasification and combustion processes can be used as a supplementary material in cement and ceramic manufacturing (Zain *et al*., 2011) and the spent material from bioconversion can be used as an animal feed (Bisaria *et al*., 1997). Nevertheless, their low heating values as well as pollution-prone attributes make the wastes less profitable materials while creating harmful effects on the environment. In principle, rice straw can be put into varied uses such as for soil fertility improvement through carbonisation and composting, in bio energy production, in the making of bio fibre and other industrially useful products.

Rice straw differs from other straws in having higher content of silica and lower content of lignin. Higher silica content was found in leaves compared to stem portion of straw. Rice straw is considered as a ligno-cellulosic biomass that contains 35-40 per cent cellulose, 25-30 per cent hemicellulose, and 10-15 per cent lignin and 6-12 per cent silica

(Thygesen *et al*., 2003). Ruensuk *et al*. (2008) found that the C: N ratio of rice straw was 61.7. Whereas, Goyal and Sindhu (2011) reported that C: N ratio of rice straw was 73.7. Compared to the biomass of other plants such as soft wood, rice straw is lower in cellulose and lignin and higher in hemicellulose content (Barmina *et al*., 2013).

The chemical composition of rice husk resembles many common organic fibers as it contains 40-50 per cent cellulose, 25-30 per cent lignin, 15-20 per cent ash and 8-15 per cent moisture (Hwang and Chandra, 1997). Rice husk is composed of 38.8 per cent carbon, 4.8 per cent hydrogen, 35.50 per cent oxygen, 0.5 per cent nitrogen, and 0.1 per cent sulphur (Jenkins *et al*., 1998). Ghatak and Mahanata (2018) studied the cellulose, hemicellulose, and lignin content of husk and straw. The rice husk contains 28 per cent cellulose, 24 per cent hemicellulose, and 25 per cent lignin. Whereas, straw contains 30.2 per cent cellulose, 35 per cent hemicellulose, and 22 per cent lignin. They also opined that C: N ratio of rice husk was high and it was found to be 81.97.

The lignin and SiO_2 content reported by Soest (2006) for rice husk and straw were 160 g kg^{-1} and 230 g kg^{-1}, and 52±16 g kg^{-1} and 130 g kg^{-1}, respectively. The ash content of rice husk and straw were 22.1 per cent and 14.61 per cent, respectively (Xu *et al*., 2012). Zhang *et al*. (2019) characterized the rice straw and husk collected from Egypt, Cuba, and China for their physical properties *viz*., moisture content, bulk density and porosity. The moisture content of collected husk and straw were in the ranges of 4.60-6.07 per cent and 6.58-6.92 per cent, respectively. They concluded that the difference in moisture content could have resulted from using different collection, storage, and drying procedures. The bulk density of rice husks and straws varied from 0.331-0.380 Mg m^{-3} and 0.162-0.194 Mg m^{-3}, respectively. The porosity of rice husks varied from 63.64-68.94 per cent and those of straws were in the range of 71.21-85.28 per cent.

The surface morphology of rice straw was studied using scanning electron microscope by Li *et al*. (2012), and they observed a dent structure and concluded that straw maintains the plant cell wall composition such as epidermis, vascular bundles, and parenchyma sticking to the bundle surface. Phutela and Sahni (2012) also studied the surface morphology of paddy straw and straw treated with *Trichoderma reesei*. The distinct changes in surface structure were visible in the basic tissue of straw. They observed a rigid and highly compact structure on the paddy straw, whereas, pre-treated samples showed opening of the holocellulose fibrils due to creation of pores of different sizes. Microfibrils were found to be separated from initial connected structure and were fully exposed thus increasing the surface area and porosity of paddy straw. Arora and Kaur (2018) opined that the straw surface was visible as coarse and long thick fibers appearing as a compact meshwork of cellulose, hemicellulose and lignin fibers appearing as a compact meshwork of cellulose, hemicellulose, and lignin fiber arranged in densely packed sheets.

The exterior surface morphology of rice husk was studied by Chen *et al*. (2017) and they observed well- arranged micro-bumps on the surface with a tip like structure on the top. They concluded that the outer epidermis was uneven and appeared to be highly ridged in structure with protrusions. Thiyageshwari *et al*. (2018) studied the physical structure of rice husk using scanning electron microscope (SEM) and they revealed that the epidermis of rice husk becomes loose, rugged and lumpy because of the composition of rice husk *viz*., cellulose, hemicellulose, lignin, and pectin. Silica is present all over the fiber, being more abundant in the protuberance and fibers of the outer epidermis. Whereas, comparatively lesser in the inner epidermis adjacent to rice kernel.

The functional groups present in the rice straw was analysed using FT-IR by Wu *et al*. (2012) and were assigned to wave numbers from FT-IR spectra as follows: 3600-3200 cm^{-1} to O-H stretching of hydroxyl groups; 2950-2850 cm^{-1} to C-H stretching of aliphatic CHx; 1740-1700 cm^{-1} to C=O stretching of carboxyl and ketones, 1630-1600 cm^{-1} to C=C stretching of aromatic components and to smaller extent to C=O stretching in quinones and ketonic acids; 1440 cm^{-1} to C=C stretching of aromatic C, and 900-750 cm^{-1} to C-H bending aromatic CH out of plane deformation. Matthews (2016) reported that the absorption bands in FT-IR spectra of rice straw are associated with the presence of ligno-cellulose content of straw. Cellulose was found by glycosidic linkages and hydroxyl groups with a small amount of carboxyl, while hemicellulose and lignin are predominated by ether bonds and carboxyl bonds.

Morcali *et al*. (2013) observed the presence of silicon in the IR spectra of rice husk in the region of 1200-1000 cm^{-1}, and are considered to be resulted from the superposition vibrations of the C-OH bond and Si-O bond in the siloxane (Si-O-Si) groups.

2.2. RESIDUE APPLICATION ON SOIL HEALTH AND CROP PRODUCTIVITY

Rice straw contains large amount of silicon that on incorporation can increase its availability in soils. According to Sumida and Ohyama (1991), application of rice straw increased the silicon content of rice plants, which helped to increase the lodging resistance in rice. Witt *et al*. (2000) reported that, nitrogen supply was greater when residue incorporation took place in 63 days rather than in 14 days before planting rice and this was also associated with greater rice yields. Bird *et al*. (2002) reported that a consistently larger soil microbial biomass N and C pool was observed when straw was incorporated than when it was burnt.

Gangwar *et al*. (2006) observed greater concentrations of plant available phosphorus when straw was incorporated compared to when it was removed in a three years of rice-wheat study. Returning straw to the field could improve soil available potassium to a significantly greater extent than manure (Kaur and Benipal, 2006).The *in-situ* incorporation of rice straw in the soil has been shown to contribute recycling of nutrients, increasing soil organic carbon and yields of subsequent crops (Bijay-Singh *et al*., 2004 and Gupta *et al*., 2007). The accumulation of residues in the soil not only reduces water loss, mitigates soil erosion and provides nutrients (Yang *et al*., 2007), but can also maintain soil nutrients, enhance soil fertility and promote the development of modern agriculture.

The C: N ratio of an organic material determines its quality, with high C: N ratio, representing low quality and slow rate of decomposition, whereas low C: N ratio representing high quality with a faster decomposition. The availability of nutrients is affected by the low quality of rice straw, with a high C: N ratio, resulting in slow decomposition and mineralization of nutrients, particularly short term availability of N and to some extent P (Thuy *et al*., 2008).

Thuan and Long (2010) conducted a study in Vietnam, where they reported an increase in soil nitrogen from 0.65 to 0.85 per cent following nine years of cropping with incorporation of rice straw while, straw removal caused decline in soil nitrogen. They also found that about 67 to 69 per cent of the rice straw had decomposed by the time the plant had reached physiological maturity.

Thanh *et al*. (2016) observed that, the requirement of nitrogen fertilizer was reduced by about 20 per cent in a long term study with straw incorporation.

Zhao *et al*. (2019) investigated the effects of straw incorporation on soil fertility and crop yield in rice-wheat rotation on sandy loam soil with two treatments *viz*., straw removal and straw incorporation. They observed that full straw incorporation markedly increased the soil N, P, K, soil organic carbon, cation exchange capacity, water holding capacity, soil microbial biomass, enzyme activities and finally the crop yield.

Ogbe *et al*. (2015) concluded that the application of rice husk from 0 to 6 t ha^{-1} significantly increased the soil pH, total porosity, organic matter, exchangeable bases (Mg^{2+}, K^+, and Na^+) and cation exchange capacity while, bulk density and electrical conductivity decreased between treatments.

2.3. RICE RESIDUE MANAGEMENT

The management of crop residues is a key component of sustainable cropping systems and it has received much interest in recent years as a means of increasing soil organic matter and nutrient supplying capacity, and reducing the ill effects of residue burning. Proper management of residues is very essential because these residues serve as good source of plant nutrients.

Incorporation of crop residues can change microbial processes, which affect nutrient availability and hence crop yield. Soil microenvironments for biological and chemical processes differ in surface placed than in incorporated residues thereby influencing the nature and extent of organic matter dynamics and nutrient cycling (Cookson *et al*., 1998).

Incorporation of crop residues into the soil is a common management option, but adequate time is required for the decomposition due to high C: N ratio. Landfilling and open burning of rice residues are widely practiced in developing countries, leading to severe air, land, and water pollution as well as detrimental effects on air quality and human health (Sim and Wu, 2010). In light of these pollution issues, new ways to manage and utilize agricultural wastes for the beneficial purpose are the need of the hour. Therefore, it is important to look for sustainable solutions and technologies that can reduce the environmental foot print and add value by increasing the revenues of rice production systems. Among the waste utilization strategies, composting and production of biochar are proven “waste to wealth technologies”.

2.3.1. Composting

Composting is the biological decomposition of organic waste by bacteria, fungi, worms, and other organisms under controlled conditions into humus rich, relatively bio-stable product which can be used to improve soil properties and augmenting crop growth and productivity.

Composting rate depends to a great extent on C: N ratio, lignin and polyphenol contents, presence or absence of suitable microbial agents of decomposition, pH, temperature, aeration, moisture content, *etc*. Almost all organic materials are suitable for composting.

Chandna *et al*. (2013) opined that during the composting of agricultural substrates, organic C decreased, whereas total N, P and K increased with time. Finally C: N ratio was observed to be stabilized at 11:1 at the end of composting during 40–50 days. The decrease in organic carbon was due to evolution and volatilization of CO_2 through the biodegradation process by aerobic heterotrophic microorganisms. Compost is considered as mature when it C: N ratio was approximately 17 or less, unless ligno-cellulolytic materials remain on the substance (Moldes *et al.*, 2007and Al-Barakah *et al*., 2013).

Vermicomposting is the mesophilic oxidative conversion of organic matter to mucus coated granular worm casts through the combined action of microorganisms and earthworms. Vermicompost is a finely divided, peat like material with high porosity, good aeration, drainage, water holding capacity, microbial activity, and excellent nutrient status and buffering capacity which makes its application congenial for soil fertility and plant growth. Lee (1985) pointed out that the improvement in soil structure following worm cast application may significantly enhance plant growth.

2.3.1.1. Characterization of compost

Vermicompost is a stabilized, homogeneous, odour free, peat like material containing significant quantities of nutrients with low level of toxicants.

Kaviraj and Sharma (2003) observed an increase in electrical conductivity during vermicomposting. They concluded that this might be due to the release of different soluble mineral salts in available forms and organic matter degradation.

Nitrogen increase after vermicomposting may probably be due to two factors, 1) reduction in organic carbon in terms of carbon dioxide and 2) addition of nitrogen by earthworms in the form of mucus, nitrogenous excretory substances, growth stimulating hormones and enzymes (Tripathi and Bhardwaj, 2004). In addition to this, nitrogen may also be added by organic matter mineralization by earthworm activity.

Increase in potassium and phosphorus content in vermicompost may be due to the enzymatic activities of earthworm gut and its deposition in the vermicasts (Pramanik *et al*., 2007).

Deka *et al*. (2011) reported that vermicompost has significant level of nitrogen rich compounds and low level of aliphatic/aromatic compounds as compared to the initial level of the biowaste materials, which was confirmed by FT-IR analysis.

Mainoo *et al*. (2009) reported that earthworms do not affect the pH of organic substrates but they do exert physiological control such as secreting intestinal calcium and excreting NH_4-N for maintaining the neutral pH in their digestive tracts. Variation in the pH during vermicomposting depends on the chemical quality of the feedstock. The change in pH of the substrates during decomposition was due to microbial conversion and subsequent release of organic acids and ammonia from residues (Bisen *et al.*, 2011).

The presence of calciferous gland in most of the epigeic earthworms might result in the increase of Ca in the produced vermicompost. A common feature of this structure is the release of calcareous secretion which would be deposited as calcite in the oesophageal pouches (Briones *et al*., 2008). The calcite would then be released into the gut of the earthworms. Through the secretion of calcium carbonates, the earthworms control their dietary intake of calcium, allowing them to survive in various environments.

C: N ratio directly reflects the quality and maturity of the vermicompost and hence can be used as a universal parameter to assess the vermicompost quality. Reduction in C: N ratio is an indication of increased humification rate of organic matter (Parthasarathi *et al*., 2016). A remarkable decrease in the C: N ratio was noticed by Thiyageshwari *et al*. (2018) during rice husk composting and they concluded that the improvement in nitrogen and lowering of organic carbon resulted in the lowering of the C: N ratio, which is an important indicator of a compost attaining full maturity and an adequate predictor of the impact of organic amendments on nitrogen cycling once incorporated in soil.

Scanning electron micrograph of rice straw showed more compact and aggregated biomass. Change in surface morphology of residues after vermicomposting clearly depicts that earthworm activity brings out decomposition and fragmentation making vermicompost more homogeneous and porous (Lim and Wu, 2016).

Changes in physical structure of rice husk before and after composting were studied by Thiyageshwari *et al*. (2018), and they pointed out that many silica bodies which were found on the strand of rice husk at the initial stage were removed when composting was achieved.

2.3.1.2. Effect of compost on soil health and crop productivity

Vermicompost has a tremendous potential to supply plant nutrients for sustainable crop production. Enhanced nutrient supply is the result of increased microbial activity occurring in the intestine of earthworms which is subsequently excreted through earthworm gut. Thus, vermicompost addition increases the quality and quantity of nutrients resulting in quick absorption of nutrients which in turn will increase the growth and yield parameters of crop production.

Anda *et al*. (2008) from an investigation on the application of rice husk compost in an oxisol could get significant increase in soil pH, Ca, Mg, K, Na, and Si in soil. He also observed an increase in growth of Cacao plant up to 37 per cent due to rice husk application.

Badar and Qureshi (2014) reported the effect of composted rice husk on growth and biochemical parameters of sunflower plants. They concluded that composted rice husk improved the soil fertility which enhanced the total carbohydrate and protein content in sunflower plants. Shak *et al*. (2014) concluded that rice straw amended by two parts of cowdung slurry provided the best quality vermicompost with the highest content of calcium, magnesium, phosphorus, and potassium.

The application of composted rice husk significantly increased the organic carbon content of both top soil and sub soil and also increased the concentration of Ca, S, Mg, and Si in soil (Anda and Shamshuddin, 2015). Rice husk compost application improved soil quality and tomato yield in green house. The soil properties like organic matter, available P, exchangeable Mg and K were also increased (Demir and Gulser, 2015).Vermicompost or FYM application along with inorganic fertilizers stimulated the activities of soil enzymes like urease, phosphatase, and dehydrogenase at a higher rate than that of biochar (Sarma *et al*., 2017).

Thiyageshwari *et al*. (2018) pointed out that the combined application of composted rice husk at 5t ha^{-1} with 50 per cent recommended dose of fertilizers and biofertilizers at 2 kg ha^{-1} helped to boost the pulse production.

2.3.2. Biochar production

Biochar is a carbon rich charcoal like substance created by thermal decomposition of biomass or organic matter in low oxygen conditions at relatively low temperatures (<700 °C), a process known as pyrolysis. During pyrolysis, around 50 per cent of biomass carbon is converted into biochar. Of the other 50 per cent, around two thirds get released as useful energy. Thus 1 MT of dry biomass sequesters 0.3 MT of carbon, equivalent to 1.2 MT CO_2. Thereby helping to sequester carbon from the atmosphere. Its high stability in the environment relative to other types of organic carbon substances is one of the important distinguishing properties of biochar.

It has been estimated that biochar can persist up to 13900 and 10000 years in sea and soil environments, respectively (Masiello and Druffel, 1998). However, long term simulations have biochar-C can reside for 100 to 2000 years which may vary based on the location, soil, agro-climate and various agronomic management factors employed for crop production. Therefore, biochar addition to soil can provide a potential sink for carbon thus reducing the CO_2 release back to the atmosphere.

Biochar is a fine grained, highly carbonaceous, pyrolysed product of biomass or biowastes that are distinguished from charcoal by its use as a soil amendment. The use of biochar as a soil amendment has received attention owing to its potential to improve physical and chemical soil properties as well as contributing towards soil carbon sequestration. Due to the relatively stable biological state of biochar, its production for soil application has been proposed as a way of diverting waste biomass carbon from a rapid to slow carbon cycling pool in soil.

2.3.2.1. Characterization of biochar

The properties of biochar vary substantially depending on the source of biomass, the temperature at which it is heated and the extent to which produced volatiles are separated from it.

Wu *et al*. (2012) showed that pyrolysis temperature had a greater influence than residence time on the chemical composition and structure of rice straw derived biochar produced at low heating rate. They also pointed out that rice straw derived biochars especially produced at 400 °C had high alkalinity, cation exchange capacity, high level of available phosphorus and extractable cations. The stability of biochar may be increased for two reasons: first, the refractory forms of graphene –C might indicate the more graphene-like structures contributing to higher stability; second, the possibility of accelerated decomposition caused by non-aromatic fraction of biochar through co-metabolism might be declined.

Biochar yield from rice straw was 29.7 per cent on an average with an ash content of 34.2 per cent, bulk density of 0.75 Mg m^{-3}, pH (9.3) and high P (738 mg kg^{-1}). The CEC was high (44.2 cmol (+) kg^{-1}) and was also rich in exchangeable bases mainly K as compared to Ca and Mg (Kamara *et al*., 2015).

Biochar from wood (WB), bamboo (BB), and rice husk (RHB) were compared for its properties by Akshatha (2015) and concluded that, maximum water holding capacity was observed in WB (21.031 %), followed by RHB (131.41 %) and BB (93.71 %). Higher exchangeable bases, Mn, and Cu were recorded in WB while higher P, Si, Zn and Fe were recorded in RHB.

Increasing pyrolysis temperature during biochar production results in the dehydration of hydroxyl groups and thermal degradation of cellulose and lignin (Zhang *et al*., 2015).

Sun *et al*. (2017) reported that the yield of biochars on dry ash free basis were positively correlated with cellulose, lignin, and lignin/cellulose content of feedstock. The fixed carbon content in biochar was also negatively influenced by ash content of feedstock, and it increased with increasing pyrolysis temperature when the ash content was below 34.57 per cent in feedstock and decreased when the ash content exceeded. The contents of cellulose, lignin, and lignin/cellulose in feedstocks were positively related to fixed carbon production in biochar. Fixed carbon generation was higher in the feedstock which had more lignin content as compared to cellulose. The lignin is more thermally stable than cellulose during pyrolysis; thus the production of fixed carbon in biochar increased with increase in lignin / cellulose content in biomass.

The surface morphology of rice husk biochar was studied by Milla *et al*. (2013), and the SEM-EDX analysis showed that the microstructure of the rice husk biochar was highly heterogeneous. Rice husk biochar particles consisted of higher silicon mineral agglomerates on lower carbon content fibers with structures typical of its biomass origin. They exhibited a large degree of macro-porosity in the 1 to 10 micron scale, with contents of carbon, oxygen, and potassium. Scanning electron microscopic images of straw and husk before and after pyrolysis were studied by Phuong *et al*. (2015) and analysis data indicated that the volatile compounds released during the pyrolysis process, created pores in the pyrolysis product. Higher macropore volume was observed in rice straw biochar than the rice husk biochar.

Keiluweit (2010) has reported that, with increasing charring temperature, strong peaks from cellulose started loosing its intensity progressively, thus getting broader, indicating a gradual decrease in cellulose content. Wu *et al*. (2012) observed that with increasing charring temperature, bands due to O-H stretching (3200-3600 cm^{-1}) and aliphatic C-H stretching (2950-2850 cm^{-1}) looses their intensity, but bands arising from aromatic C-H out of plane vibration (700-900 cm^{-1}) became more apparent. They also concluded that the formation of intermediates and increased aromatization occurred when straw was heated to 400-500 ºC. The FT-IR spectra indicate that biochar is dominated by functional groups typical of oxygenated hydrocarbons, reflecting the carbohydrate structure of cellulose and hemicelluloses (Ghani *et al*., 2013). The pyrolysis process can cause the disappearance of absorption bands characteristic of raw material and the appearance of new bands typical of biochar samples.

Abdulrazzaq *et al*. (2014) reported that the peaks between 2932 and 2880cm^{-1} assigned to aliphatic C-H stretching vibration present in the residues, were not detected in RHB indicating that labile aliphatic compounds got decreased after charring. On the other hand, peaks between 1648 and 1540 cm^{-1}showed a high intensity region C=C stretching; expressive of an increase in aromatic components during gasification Wang *et al*. (2018) studied the structural characteristics of straw and husk biochar, and they reported that the band at 1092 cm^{-1}, 782 cm^{-1} and 471 cm^{-1} were assigned to the Si-O-Si groups.

2.3.2.2. Effect of biochar on soil health and crop productivity

Biochar, a by-product of organic matter pyrolysis, improve soil physical and chemical properties and enhance carbon sequestration (Glaser *et al*., 2002). The bulk density of biochar is much lower than that of mineral soils and its application decreased soil bulk density (Gundale and De-Luca, 2006). Biochar, being recalcitrant to microbial decomposition provide long term benefits to soil fertility (Steiner *et al*., 2007).

An increase in soil CEC with the application of rice husk biochar has been reported by Chan *et al*. (2007). The significant increase in CEC of soils with the application rice husk biochar would probably be due to the negative charge arising from the carboxyl groups of the organic matter. The aromatic structure and presence of highly stable carbon in biochar provides resistance to microbial mineralization thereby reducing the CO_2 emission from the soil (Lehmann *et al*., 2011).

Biochar application significantly enhanced the aggregate stability indices of the clay soil mainly consisting of silt and clay particles but had no effect on the loamy sand with more sand content (Herath *et al*., 2013).

A field experiment was carried out by Islam *et al*. (2013) to study the yield stability of cassava + peanuts intercropping system after three years of biochar application. The experimental results showed that the application of biochar increased and stabilized land use efficiency of cassava + peanuts intercropping.

Milla *et al*. (2013) reported that the application of rice husk biochar increased biomass production of water spinach in a field experiment. Kamara *et al*. (2015) reported that plant height and tiller number of rice were improved after eight weeks of rice straw biochar application.

According to Lu *et al*. (2014), rice husk biochar increased macro-aggregates and reduced micro-aggregates. They reported that rice husk biochar amended soils had higher mean weight diameter, water holding capacity, porosity and higher available water content whereas the tensile strength and coefficient of linear extensibility had reduced due to its application as compared to control in clayey soil. They also concluded that it could act as glue between macro and micro-aggregates. The elevation in soil pH brought about by its liming properties remained as an added advantage.

According to Prommer *et al*. (2014) biochar application increased total soil carbon but decreased the extractable organic carbon pool and soil nitrate. He also concluded that the single or combined application of biochar in combination with any organic fertilizer may increase the soil organic nitrogen which may enhance the soil carbon sequestration and thereby, could play a significant role in future environmental management planning.

Abrishamkesh *et al*. (2015) revealed that rice husk biochar application resulted in increased soil organic carbon, cation exchange capacity and available potassium.

Dong *et al*. (2015) demonstrated that application of rice straw biochar enhanced the rice production and nitrogen retention in a waterlogged paddy field.

Alkaline biochar was used as a soil amendment for neutralizing acidity, improving soil fertility and sequestering carbon in acidic soils (Kuppusamy *et al.*, 2016).

Akshatha (2015) reported that application of RHB increased straw yield by 55.18, 27.64 and 28.84 per cent in alkaline, neutral and acidic soils, respectively. Corresponding increase in rice grain yield was 12.78, 28.29 and 46.47 per cent. Increase in rice grain yield as a result of co-application of rice straw biochar and compost was also remarked by Sadegh-Zadeh *et al*. (2018).

Cui *et al*. (2017) found a significant reduction in methane emissions, global warming potential and greenhouse gas intensity when a cold water logged paddy field was applied with 2 t ha^{-1} of rice straw biochar in North China. The addition of biochar in acid soil would be a sustainable option to reduce C mineralization in addition to managing soil nutrient status (Sarma *et al.*, 2017).

Changes in water holding capacity by soil amendment was primarily due to the water holding capacity characteristic of the rice husk biochar itself. This was evident in the study conducted by Persaud *et al*. (2018), where the highest rate of biochar application (50 t ha^{-1}) had the highest percentage of organic matter (3.59 %) and recorded the greatest improvement in water retention. They also reported a significant increase in pH, organic carbon, organic matter, cation exchange capacity and decrease in soluble iron content in soil.

Biochar application increased the maximum allocation of carbon both in the soil and biomass, thus protraying its carbon sink capacity (Rajalekshmi, 2018). She also concluded that the alkaline biochar can be considered to reclaim acidity instead of lime in acid soils of Kerala.

Application of rice husk biochar had a positive effect on soil properties, aggregation, and nitrate retention of soil (Ghorbani *et al.*, 2019).

2.4. CARBON SEQUESTRATION

Carbon sequestration is a process of relocating atmospheric CO_2 into other long-lived global pools such as oceanic, pedologic, biotic and geological strata (Lal, 2008). Even though the fact that the agricultural soils are considered as a source of GHG emission, its potential role as a sink cannot be deserted. Carbon sequestration is one of the most assuring approaches to minimize the GHG emission while safeguarding the C in the permanent pools of soil strata.

The high productivity, high water table, and low decomposition rate associated with wetlands favour carbon storage within the soil, sediments and detritus (Whitting and Chanton, 2001). In general, rice soils are known to retain higher amounts of resilient carbon among all terrestrial ecosystems (Xie *et al.,* 2007). As a result of submerged conditions, organic matter preferentially accumulates in continuous rice systems. Slower decomposition of organic matter and higher net productivity of submerged paddy soils lead to net carbon accumulation. In submerged soils, the formation of recalcitrant complexes with organic matter renders them less available for microbial attack. Moreover, the biological nitrogen fixation coupled with overall higher primary productivity and decreased humification lead to net accumulation of organic matter in wetland soils and sediments. Consequently, a long period of soil submergence promotes the formation of passive pools of SOC vis-a-vis carbon sequestration (Mandal *et al.,* 2008). In contrast, the formation of humic compounds is maximized under partly oxidizing conditions: If there is too much oxygen, full mineralization occurs; if there is too little, oxidative polymerization is stifled.

2.4.1. Carbon sequestration as affected by management practices

Follett (2001) reported that the application of manure in the soil would result in SOC sequestration at the rate of 200 to 500 kg C ha^{-1} year $^{-1}$. According to the Intergovernmental Panel on Climate Change (IPCC, 2000), enhanced crop management in the world scale can sequester 125 MMT by 2010 and 258 MMT of SOC in 2040.

Benbi and Yadav (2015) studied the decomposition of rice straw (RS), rice straw derived biochar and compost (RSC), rice husk (RH), rice husk ash (RHA), and farmyard manure (FYM) in laboratory incubation experiment. The proportion of antecedent C mineralized from different sources followed the order RS>RH>FYM>RSC=biochar>RHA. It was concluded that RS and RH could result in short term carbon accrual in soil, whereas RSC, biochar, and FYM may lead to long term carbon sequestration.

Sarma *et al*. (2017) reported that application of vermicompost and FYM enhanced the activities of soil enzymes and carbon mineralization rate while biochar application noted higher C half-life and soil pH.

Hossain *et al*. (2017) reported that maximum CO_2 emission loss was found in chicken manure mixed soil followed by rice straw and rice husk biochar. Therefore, the application of rice husk biochar improves the soil health and reduces CO_2 emission from agriculture soils.

Thus, climate smart soil management practices might help in reducing CO_2 emission from soil.

2.5. CHEMISTRY AND TRANSFORMATION OF NUTRIENTS IN LOWLAND RICE

Asian lowland rice cultivation contributes significantly to global rice supplies. More than 70 per cent of rice in Asia is produced in lowlands with irrigation. Rice being a sub-aquatic plant could derive benefits from submerged conditions (Kamoshita, 2007). This is due to the presence of aerenchymatous tissues conduiting air from leaves to root.

Water logged soils are subjected to flooded or anaerobic condition for a long period of time. These soils have distinctive gley horizons due to redox reactions. This resulted in (a) partially oxidized horizon (b) a mottled horizon and (c) a reduced horizon. A variety of electrochemical changes occurs under submergence. These include a) decrease in redox potential, b) an increase in pH of acid soils and decrease in pH of alkaline soils, c) changes in specific conductance and ionic strength, d) drastic shifts in mineral equilibria, e) cation and anion exchange reactions, and f) sorption and desorption of ions **(**Ponnamperuma, 1972).

Redox potential (Eh) is the electro-chemical property that serves to distinguish a submerged soil from a well-drained soil. When an aerobic soil is submerged, Eh decreases during the first few days and reaches a minimum, then it increases, attains a maximum, and decreases asymptotically to a value characteristic of the soil, after 8-12 weeks of submergence (Ponnamperuma, 1972).

In submerged soils, nitrogen mineralization stops at ammonium production due to absence of oxygen. In flooded soils, ammonium is produced by reductive deamination and purine degradation. This causes release of ammonia, carbon dioxide and volatile fatty acids. The ammonium being stable under anaerobic environment readily accumulates (Ponnamperuma, 1972).

The phosphorus availability to rice increases upon submergence and is brought about by an increase in pH of acid soils and decrease of pH of alkaline soils. Decrease in redox potential and reduction of iron phosphates resulted in increasing phosphorus availability in acidic soils. Whereas, decrease of pH in alkaline soil under submergence increases the availability of phosphorus resulting from the solubilisation of tricalcium phosphate. The availability of phosphorus is maximum in neutral range.

The bioavailability of K, Ca and Mg is increased upon flooding. Since Fe and Mn are the dominant cations in the acidic soil environment the competition of K, Ca and Mg with Fe^{2+} and Mn^{2+} results in low plant uptake of K, Ca and Mg (Fagaria *et al.*, 2008).

Upon submergence, reduction of SO_4^{2-} to S^{2-} occurs. Also, there is dissimilation of amino acids to hydrogen sulphide and ammonia (Ponnamperuma, 1972).

Iron is a major constituent of most soils. The Fe^{3+} ion is reduced to Fe^{2+} due to oxidation-reduction processes, which enhances its uptake.

The manganic (Mn^{4+}) form of manganese is reduced to manganous (Mn^{2+}) form upon submergence. This causes an increase in manganese availability.

There is an increase in amorphous sesquioxides form and a decrease of water soluble, exchangeable and crystalline sesquioxide bound form of zinc (Hazra *et al.*, 1987). Hence zinc deficiency is widespread under lowland rice systems.

Copper availability is decreased due to precipitation of solubilized copper as copper sulphide. The formation of insoluble complexes with organic compounds in organic soils also resulted in copper deficiency.

The organic matter decomposition in a flooded soil is slower and the end products of decomposition are different from that of aerobic soils. The decomposition of organic matter is triggered by the facultative and obligate anaerobes in a submerged soil. The anaerobic bacteria being operating at a lower level of energy than aerobic bacteria, decomposition processes are slower than in flooded system. (Ponnamperuma, 1972). The main end products of anaerobic decomposition are: CO_2, H_2, CH_4, NH_3, H_2S, *etc*.

2.6. FRACTIONS

2.6.1. Fractions of carbon

Soil constitutes the largest dynamic reservoir of carbon on earth which makes it a critical component of the global carbon cycle. In soil, the carbon is mostly bound with soil organic matter consisting of the dead biomass from roots, plant litter, animals and microorganisms along with the live organisms which actively consume and produce a diverse mixture of carbon containing compounds.

It is the biogeochemical cycle of carbon in the earth system that controls the fluxes, pools and transformations associated with this most fundamental element. In order to characterize the amount of carbon stored in the given reservoir, be it atmosphere, terrestrial or aquatic, the time needed to exchange each carbon atom of the system otherwise called as mean residence time and also the physical or chemical state of carbon in a given reservoir or as it exchanges among the reservoirs are essential to be characterized. Based on the mean residence time, a particular system can be further divided into active/labile pool (1-5 years MRT), slow pool (20-40 years MRT) and passive/inactive/recalcitrant pool (200-1500 years MRT). In general, the labile carbon pool has a greater turnover rate (shorter MRT) of several weeks / months / years as against the recalcitrant pools and thus the labile pools like microbial biomass carbon (MBC), water soluble carbon (WSC), hot water soluble carbon (HWSC), light fraction carbon (LFC) and particulate organic matter (POM) has been suggested as early indicators of the effects of land use changes on SOM quality (Gregorich *et al*., 1994; Bolinder *et al*., 1999; Paul *et al*., 2001; Ghani *et al*., 2003; Banger *et al*., 2010).

Water soluble carbon (WSC) is considered as the most mobile and labile component of soil organic matter. Although it accounts to a smaller part of soil organic matter, it contributes significantly to the nutrient cycle and is the main energy substrate for soil microbes (Qualls *et al*., 1991).

The hot-water extractable carbon (HWEC) is a sensitive indicator of the ecosystem changes. Being a component of the labile SOM and also being closely related to soil microbial biomass and micro aggregation it can be used as one of the soil quality indicators in soil plant continuum. This fraction extracted after WSC, using hot distilled water extracts soil microbial biomass, simple organic compounds and compounds which are hydrolysable under the given extraction conditions (Weigel *et al*., 2011). Plenty of literature designates its extraction as near to nature conditions of the ongoing mineralization process.

Microbial biomass carbon (MBC) is a measure of the carbon contained within the living component of soil organic matter. Microbes decompose soil organic matter releasing carbon dioxide and plant available nutrients. Because of its high turn-over rate, microbial biomass carbon responds more rapidly to changes in soil microclimate than soil organic matter (Powlson *et al*., 1987). Microbial biomass carbon is the labile pool in soil and therefore, the nutrient availability and productivity of agro ecosystems mainly depends on their size and activity (Friedel *et al.*, 1996). Soil microbial biomass carbon comprises 1-5 per cent of total organic carbon (Zhang and Zhang, 2003).

Permanganate oxidizable carbon (POXC) measurement is based on chemical oxidation of organic matter by a weak potassium permanganate solution. It includes all readily oxidizable organic components including humic materials and polysaccharides, which generally accounts for 5-30 per cent of SOC (Blair *et al.*, 1995; Gragham *et al.*, 2002). The turnover time of POXC is shorter and is hence more sensitive to management practices (Andrews *et al.*, 2004).

An information on total carbon which is the summation of three carbon forms namely organic, elemental (which is insignificant in most soils) and inorganic (usually carbonates and bicarbonates) is essential for understanding the different components of SOM. Generally, in lateritic soils, the content of total carbon almost equates with the organic carbon.

The labile SOC pools such as water-extractable organic C, hot water-soluble organic C, potassium permanganate oxidizable organic C, and organic C fractions of different oxidizability are considered to respond to agricultural management rapidly than total carbon (Blair *et al.*, 1995; Benbi *et al.*, 2012).

2.6.2. Fractions of nitrogen

Nitrogen is one of the most important macronutrient and is a major component of cholorophyll. Approximately, 90-95 per cent of soil nitrogen is in organic form but the plant depends on the inorganic nitrogen sources though it accounts only 5-10 per cent. Among the inorganic forms of nitrogen, nitrate-N is the most abundant form in aerobic environment and ammoniacal-N in submerged condition.

The organic forms of soil nitrogen occur in various stages of humification and decomposition and are closely related to the microbial activity. This in turn contributes to the net release of nitrogen from the organic reserve as mineral nitrogen (Gotoh *et al.*, 1986). The total hydrolysable nitrogen contributed to about 80 per cent of total nitrogen (Mini, 1992). Hydrolysable nitrogen decreased gradually with the progress of humification.

Soil characters and conditions were found to influence the amino acid fraction of the hydrolysable nitrogen. Considerable quantity of nitrogen in hydrolysable nitrogen is in amino acid form. Ramamoorthy and Velayutham (1976) concluded that about 18-30 per cent of the total nitrogen in most of the surface soils occurred as bound amino acids. The organic matter content affects the distribution of amino acid in soil. Soil organic nitrogen plays a significant role in nitrogen retention and transformation. Nitrogen availability, which is important for the growth of plant are closely associated with the mineralization of soil organic nitrogen and the depolymerisation of the nitrogen containing constituents (Lu *et al*., 2018).

2.6.3. Fractions of phosphorus

Phosphorus is a major component of ATP, often designated as the energy currency. Phosphorus vital to plant growth and it exists in the soil both in organic and inorganic forms. The different fractions of phosphorus in soil are the inorganic-P, organic-P, and total-P. Plants utilise phosphorus in the form of $H_2PO_4^-$ and HPO_4^{2-}. The inorganic phosphorus fractions seen in soil include: soluble-P, Al-P, Fe-P, Sesquioxide occluded-P, and Ca-P. Inorganic P in wetland soils are predominantly present in the form of precipitates with Ca, or adsorbed onto aluminium and iron oxides and hydroxides (Goldberg and Sposito, 1984).

Changes in pH and Eh caused by wet-dry soil conditions influence the availability of P because they control the P sorption characteristics of soils (Krairapanond *et al*., 1993). The increased solubility of P by reduction under submergence was noted by Valencia (1962). The concentration of P in soil solution increases initially after submergence and then decreases (Ponnamperuma, 1965; Ponnamperuma, 1972; Narteh and Sahrawat, 1999). The initial increase in soil solution P in submerged soils is linked to the transformations of Fe and changes in pH. Quintero *et al*., (2007) suggested that changes in P fractions as a result of anaerobic conditions were related to soil carbon, pH and soluble and weakly adsorbed Fe. Geetha (2015) reported that the major fractions which contributed to available P in soil under flooded condition were Fe-P, Al-P and sesquioxide occluded P. The decrease in the distribution of above mentioned fractions from initial status to harvest stage of rice were counterpoised by the corresponding increased percentage distribution of Ca- P from an initial status to harvest of the crop.

Ch’ng *et al*. (2014) conducted an incubation experiment to investigate the effect of organic amendments including biochar on P fractions. Amending soil with sole biochar or compost or its combined application was found to increase total P, available P, inorganic P fractions (soluble inorganic P, Al bound inorganic P, Fe bound inorganic P, redundant soluble inorganic P, and Ca bound P), and organic P. The increase in P fractions were ascribed to increased soil pH and reduced exchangeable Fe and Al, following biochar application.

2.6.4. Fractions of potassium

Potassium is present as soluble cation in soil solution and its concentration is dependent on the type of clay, water content, intensity of leaching, and the amount of exchangeable- K. Both readily exchangeable-K and water soluble-K contributes to available potassium. As mineral potassium is the major contributor to the total soil potassium, soils containing more amount of potassium bearing minerals like mica and feldspar and the clay minerals like illite results in more total potassium in soil.

Kaur and Benipal (2006) reported that the application of rice straw increased water soluble and total potassium than control and FYM treated soils. Rice straw application either alone or in combination with FYM significantly improved total, water soluble, exchangeable, non-exchangeable and fixed K over inorganic and FYM alone treatments (Yadav, 2014).

2.6.5. Fractions of calcium

Calcium is the fifth most abundant element in earth's crust and is the most dominant cation in the exchange complex of soil colloids. Water soluble, exchangeable and total calcium are the different calcium fractions in soil. The status of available calcium is critically low in soils of Kerala due to heavy losses of these ions as a result of high rainfall.

Bhindhu (2017) concluded that the per cent distribution of exchangeable calcium was more than water soluble calcium and the path coefficients of different fractions of calcium revealed that the solid phase of calcium controlling the availability of calcium in soil is the exchangeable fraction. All other fractions influence the available pool positively through the exchangeable fraction.

2.6.6. Fractions of magnesium

Magnesium is the eighth most abundant element in earth's crust and is a structural component of chlorophyll. Different forms of magnesium in soil include water soluble, exchangeable and total magnesium. Magnesium mainly occurs in non-exchangeable forms as silicate minerals with smaller amount present as exchangeable and water soluble forms and a small fraction held within soil organic matter. Exchangeable magnesium is always present in smaller quantities than calcium.

Availability of magnesium to plants depends on the form and quantity of magnesium in soil. Generally, magnesium is low in Kerala soils because of the losses occurring due to high rainfall. Bhindhu (2017) observed that contribution of exchangeable magnesium was more than the water soluble magnesium into the total magnesium fraction. The water soluble and exchangeable fractions are the immediate nutrient reservoir for plants.

2.6.7. Fractions of sulphur

Sulphur in soils is present in both inorganic and organic forms and the proportion of inorganic to organic sulphur varies widely depending upon the nature of soil, its depth and management factors to which the soil is subjected. Inorganic S composed of water soluble and adsorbed sulphate, is generally believed to be the immediate source for plants. Generally, it accounts for less than 5 per cent of total soil S. In soil solution, sulphate is present only in small quantity which varies continuously and its concentration at a particular time depends on the balance between plant uptake, fertilizer input, mineralization and immobilization. Total soil sulphur comprises inorganic and organic binding forms.

Mineralisation of the sulphur pool in the paddy soils were studied by Zhou *et al.* (2005) and was found that the major fraction of the S mineralised was originated from the S bonded with carbon and the organic S pool which cannot be reduced.

In an experiment in the paddy soils of Uttar Pradesh by Singh *et al.* (2012), different pools of S were estimated with the help of suitable extractants. The average value of total S was 434.4 mg kg^{-1} soil, while that of organic S was 250.2 mg kg^{-1} soil. Different pools of sulphur were positively correlated with the organic carbon, clay content and available nitrogen.

2.6.8. Fractions of silicon

Silicon is the second most abundant element in the earth’s crust (28 %) and is considered as a beneficial nutrient. The contents of silicon in plants are comparable to the levels of many macronutrients. However, silicon is not considered as an essential nutrient for plant growth (Epstein, 1994). Plants with silicon content greater than one per cent are considered as silicon accumulators. Generally, graminaceous plants take up higher amount of silicon as compared to other plant species and few dicotyledons, including legumes, are considered as silicon excluders (Ma *et al.*, 2001). It has been widely accepted that rice is a silicon accumulating plant (Rao *et al*., 2017).

Monomeric form (H_4SiO_4) is the plant available form of soil silicon. The solubility of silicon in soil is affected by a number of dynamic processes occurring in the soil including the particle size of silicon fertilizer, soil acidity, organic complexes, presence of aluminium, iron, and phosphate ions, dissolution reactions and soil moisture. Georgiadis *et al.* (2013) partitioned silicon in soil into mobile silicon, adsorbed silicon, organic silicon, occluded silicon, and amorphous silicon.

The amorphous silicon fraction includes minerogenic and biogenic silica. The minerogenic amorphous silica corresponds to the non-crystalline inorganic fraction such as silicon included in iron oxides/hydroxides and silicon in inorganic alumina-silica coatings. Biogenic silicon fraction in soil is composed of phytoliths and microorganism remains *viz.*, diatoms and sponge spicules (Sauer *et al.*, 2006: Sommer *et al.*, 2006). Mobile silicon represents the immediately available silicon fraction of the readily soluble silicon. Adsorbed silicon is the immediate insoluble source of silicon in soil solution. This fraction constituted the silicic acid adsorbed by the soil minerals. The adsorption depends on soil reaction, soil composition and specific surface area of the soil particles. Silicon in soil organic matter is obtained through destruction of soil organic matter. Occluded silicon is the fraction of silicon which is associated with pedogenic oxides and hydroxides in soil. These forms seen abundant in soil plays an important role in the adsorption, occlusion, and release of silicic acid in soil. The remaining unknown mineral fractions are together known as residual silicon.

The study conducted by Lekshmi (2016) on silicon fraction in major rice growing soils of Kerala showed that residual and amorphous fractions were the most dominant silicon fractions and adsorbed silicon was the least. Silicon fractions in lateritic soil followed the order: amorphous Si> residual Si> organic Si> occluded Si> mobile Si> adsorbed Si.

MATERIALS AND METHODS

3. MATERIALS AND METHODS

Three major objectives envisaged in this research project titled “Nutrient dynamics and crop productivity in lowland lateritic soil (AEU 10) under rice residue management practices” were realised through three experiments *viz.,* characterization, incubation experiment and a field study. The experimental locations included College of Agriculture Vellanikkara, Kerala Forest Research Institute Peechi and Agricultural Research Station Mannuthy. This chapter contains the details on materials used and the methodology adopted for arriving at the results.

3.1. CHARACTERIZATION OF RICE RESIDUES AND THEIR PRODUCTS

3.1.1. Collection and characterization of straw and husk

Straw and husk are the important residues (Plate 3.1 and 3.2) produced during the cultivation and processing of rice, respectively was procured from the farmers in Thrissur district. Straw and husk required for the analysis was air dried under shade, kept in oven at 80°C, ground and sieved through 2 mm sieve and used for characterization. The details of methodology adopted for characterization are given in Table 3.1. Further materials required for the research work *viz*., vermicompost and biochar were produced from the processed straw and husk using the methodology furnished underneath.

3.1.2. Production of rice husk vermicompost

Rice husk also called as rice hull is the by-product generated in abundance from rice milling units. It contains nearly 40 per cent cellulose, 30 per cent lignin and 20 per cent silica. The richness in terms of lignin and cellulose makes difficult for its degradation under natural conditions. Their disposal in land-fill or open fields and also its burning is truly dangerous as it would cause serious environmental and human health related problems. Product diversification is an attractive texture for rice husk. As far as soil fertility restoration is concern, it is ideal to recycle this organic waste through composting. Rice husk compost as an alternative organic manure has been experimented successfully in many crops to enhance productivity.

Vermicomposting of the rice husk was carried out in the vermi unit attached to the Department of Soil Science and Agricultural Chemistry in ferrocement tanks of one meter

Table 3.1: Analytical methods employed for characterization of rice residues and their products

<table>
<tr><th>Parameters</th><th colspan="3">Methods</th></tr>
<tr><td>Moisture</td><td colspan="3">Moisture meter (Model:MB23)</td></tr>
<tr><td>Bulk density</td><td colspan="3">Cylinder method (Piper, 1966)</td></tr>
<tr><td>Particle size</td><td colspan="3">GOI, 1985</td></tr>
<tr><td>pH</td><td colspan="2">Potentiometry</td><td rowspan="2">Jackson, 1958</td></tr>
<tr><td>Electrical conductivity</td><td colspan="2">Conductometry</td></tr>
<tr><td>Total carbon</td><td colspan="3" rowspan="2">CHNS Analyzer (Model : Elementar’s vario EL cube)</td></tr>
<tr><td>Total N</td></tr>
<tr><td>Total P</td><td rowspan="4">Microwave digestion system with HNO$_3$
(Model : MARSX 250/40)</td><td>Colorimetry</td><td rowspan="2">Jackson, 1958</td></tr>
<tr><td>Total K</td><td>Flame photometry</td></tr>
<tr><td>Total Ca</td><td colspan="2" rowspan="2">ICP-OES
(Model: Optima® 8x00 series)</td></tr>
<tr><td>Total Mg</td></tr>
<tr><td>Total S</td><td colspan="3">CHNS Analyzer (Model : Elementar’s vario EL cube)</td></tr>
<tr><td>Total Fe</td><td colspan="3" rowspan="5">Microwave digestion system with HNO$_3$(Model : MARSX 250/40) followed by estimation using ICP-OES (Model: Optima® 8x00 series)</td></tr>
<tr><td>Total Mn</td></tr>
<tr><td>Total Zn</td></tr>
<tr><td>Total Cu</td></tr>
<tr><td>Total B</td></tr>
<tr><td>Silicon</td><td colspan="3">Digestion (Ma *et al*., 2002) and estimation using ICP-OES (Model: Optima® 8x00 series)</td></tr>
<tr><td>Cellulose</td><td colspan="3">Sadasivam and Manickam (1996)</td></tr>
<tr><td>Lignin</td><td colspan="3">Klason (1923)</td></tr>
</table>

diameter, 0.3m height and 300 kg capacity (Plate 3.3). The bottom portion of the tank up to one foot height was filled with a layer of coconut husk, position with their concave side facing upwards (Plate 3.4). Rice husk and cowdung was mixed in 6:1 ratio and this mixture was transferred into the ferrocement tank to form a layer of 30-45 cm thickness (Plate 3.5). Cowdung slurry was sprinkled over this layer. This process was continued till the tanks were filled to their fullest capacity maintaining a top layer of cowdung slurry and it was covered using moistant gunny bag. The material was left as such to allow partial decomposition with occasional turning at weekly interval followed by cowdung slurry application to ensure proper aeration and moisture content. After two months, the composting worm *Eisenia foetida* was introduced into the tank @ 2000 Nos. per tank (Plate 3.6). Turning was done once in five days to maintain homogeneity. Care was taken to ensure an optimum moisture content of 40 -50 per cent by sprinkling water. The material achieved the maturity by 128 days as evidenced by the change in appearance, colour and odour. Sprinkling of water was stopped at this point to enable the worm to migrate down and cling to the vermi bed. Composted material was collected from the top portion of the ferrocement tank without disturbing the vermi bed and kept in shade for two days. The composted rice husk (Plate 3.7) was sieved and stored in laboratory. The quality of vermicomposted rice husk was characterised using standard procedures (Table 3.1).

3.1.3. Production of rice straw vermicompost

The total biomass of straw, the residual by-product of rice production at harvest varies based on the cultivar, management practices and also on the cutting height followed. The ratio of straw to paddy varies from 0.7 to 1.4 on an average. The straw that is cut and remove and left over in the field can be burnt, incorporated into the soil or fed to live stock as the case may be. Burning of paddy straw is common practice followed by the farmers due to lack of options to dispose it. The smog and haze from burning not only affects the burning area but also the adjoining places as it happened with the residue burning in the fields of Punjab and Haryana. The residue burning resulted in the loss of major plant nutrients and beneficial soil flora and fauna. The rice straw, mainly ligno-cellulosic material can be efficiently recycled employing earthworms.

Vermicomposting of the rice straw was carried out in ferrocement tanks of 1 m diameter, 0.3 m height and 300 kg capacity. The bottom portion of the tank up to one foot

Plate 3.1: Rice straw

Plate 3.2: Rice husk

Plate 3.3: A view of ferro-cement tank

Plate 3.4: Layering with coconut husk

Plate 3.5: Filling rice husk and cowdung in alternate layer

Plate 3.6: Introducing compost worm *Eisenia foetida*

Plate 3.7: Vermicomposted rice husk

Plate 3.8: Vermicomposted rice straw

height was filled with a layer of coconut husk, position with their concave side facing upwards. Rice straw and cowdung was mixed in 8:1 ratio and this mixture was transferred into the ferro-cement tank to form a layer of 30-45 cm thickness. Cowdung slurry was sprinkled over this layer. This process was continued till the tanks were filled to their fullest capacity maintaining a top layer of cowdung slurry and it was covered using moistant gunny bag. The material was left as such to allow partial decomposition with occasional turning at weekly interval followed by cowdung slurry application to ensure proper aeration and moisture content. After three weeks, the composting worm *Eisenia foetida* was introduced into the tank @ 2000 Nos. per tank. Turning was done once in five days to maintain homogeneity. Care was taken to ensure an optimum moisture content of 40-50 per cent by sprinkling water. The materials gained maturity by 62 days as evidenced by the change in appearance, colour and odour. Sprinkling of water was stopped at this point to enable the worm to migrate down and cling to the vermi bed. Composted material was collected from the top portion of the ferro-cement tank without disturbing the vermi bed and kept in shade for two days. The composted rice straw (Plate 3.8) was sieved and stored in laboratory. The vermicomposted rice straw was characterised following the methodology given in Table 3.1.

3.1.4. Production of rice husk biochar

The charcoal like material obtained on burning organic residues from agricultural and forestry wastes resorting to a controlled burning process called pyrolysis would yield biochar. This stable solid material rich in carbon is capable of capturing carbon and locking it into the soil. The utilization of biochar as a soil amendment both for sequestering carbon and soil health benefits are extensively researched upon.

The biochars used in the present study was produced both from rice straw and rice husk utilising kilns specially designed and fabricated using a drum with 87 cm height and 57 cm diameter as shown in Plate 3.9. Rice husk was loaded to the inlet on the top and the process of pyrolysis was initiated using a little diesel. With the reduction in intensity of smoke produced, closed the inlet to slow down air entry thus preventing the material getting converted into ash. After two and half hour duration the kiln was allowed to cool and the finished product ‘rice husk biochar’ (Plate 3.10) was collected from the outlet located towards the bottom side. Pyrolysis temperature was recorded using an Infrared thermometer and it was found to vary between 350 to 600 °C throughout the process.

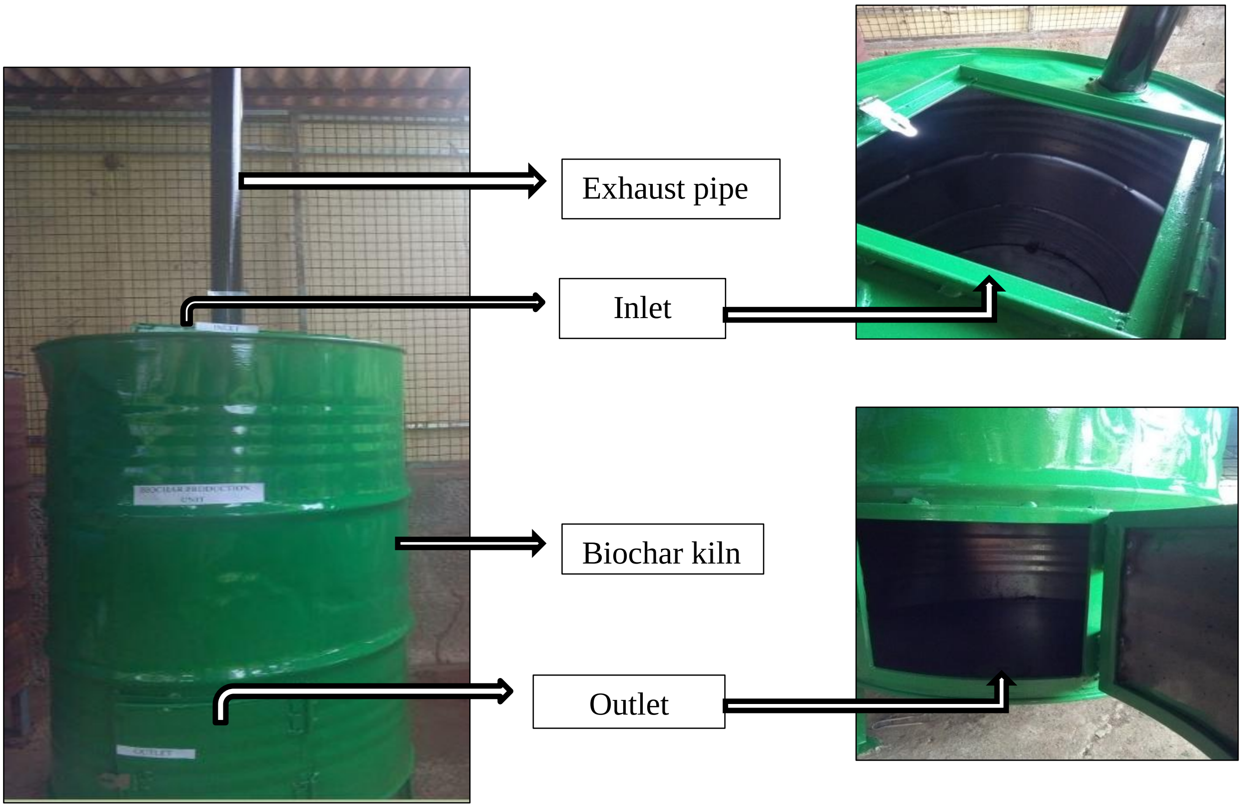


Plate 3.9: Kiln used for biochar production

Plate 3.10: Rice husk biochar

Plate 3.11: Rice straw biochar

The product was crushed and passed through 2 mm sieve and the properties were analysed using standard procedures (Table 3.1).

3.1.5. Production of rice straw biochar

Biochar from rice straw was also produced using the same kiln (Plate 3.9) as described under rice husk biochar. In case of rice straw biochar (Plate 3.11) the process was completed within an hour and after which the kiln was left for cooling. The standard procedure employed for characterising rice straw biochar are furnished in Table 3.1.

3.1.6. Surface morphology

The information on surface composition and topography of the straw and its products were studied using Scanning Electron Microscope (SEM) that enabled for creating a high resolution image. The facilities available at Central Instrumentation Laboratory, College of Veterinary and Animal Sciences, Mannuthy were made use for this purpose.

The samples were smeared on a small piece of adhesive carbon tape which was fixed on a brass stub. The samples then subjected to gold coating using sputtering unit for 10 seconds at 10 mA of current. The gold coated samples were placed in the chamber of SEM (Model: TESCANVEGA-3-LMU) and secondary electron or back scattered electron images are recorded.

3.1.6. Structural chemistry

Structural chemistry of rice residues and their products were characterized at Central Instrumentation Laboratory, College of Veterinary and Animal Sciences, Mannuthy, Thrissur, using Fourier Transform Infra-Red spectrometer equipped with Attenuated Total Reflectance (FTIR-ATR) containing diamond crystal (Model: Perkin Elmer spectrum 100 FT-IR spectrometer with ATR).

The methodology included transferring samples to the small crystal area located on the ATR top plate, followed by positioning the pressure over crystal/ sample area and applying force till the pressure gauge registered force sufficient enough to push the sample on the diamond surface. An infra-red (IR) beam with a high refractive index was then directed at a certain angle onto the optically dense diamond crystal. This reflectance helped to create an evanescent wave that extended beyond the surface of the crystal on to the sample held in contact with it. The evanescent wave got alternated in those regions of the IR spectrum where the sample absorbed energy. These alienated beam then returned to the crystal, exist via opposite side of the crystal and got directed to the detector in the IR spectrometer. The detector recorded the alienated IR beam as an interferogram signal which could be used to generate an IR spectrum.

FT-IR spectra were acquired at the middle infra-red region of 4000-400 cm^{-1}. Organic compounds have fundamental vibration bands in the mid infra-red region, because of which this region is widely used in IR spectroscopy.

3.2. INCUBATION EXPERIMENT

Incubation experiment was conducted at Kerala Forest Research Institute (KFRI), Peechi, Thrissur, using lateritic soil collected from the experimental plot (Plate 3.12) at Agricultural Research Station (ARS), Mannuthy, Thrissur (as detailed under experiment 3), for studying the kinetics of carbon mineralization.

Table 3.2. Treatment details of incubation experiment

Treatment description		
Sl. No.	**A) Sources :9**	**Notation used**
1	Absolute control	S_1
2	Soil + Rice husk	S_2
3	Soil + Rice straw	S_3
4	Soil + Vermicomposted rice husk	S_4
5	Soil + Vermicomposted rice straw	S_5
6	Soil + Rice husk biochar	S_6
7	Soil + Rice straw biochar	S_7
8	Soil + Farm yard manure	S_8
9	Soil test based nutrient recommendation	S_9
Sl. No.	**B) Temperature :4**	**Notation used**
1	15 °C	T_1
2	25 °C	T_2
3	35 °C	T_3
4	45 °C	T_4

Design : Factorial CRD

Treatment combinations (Table 3.3): 36 (9 x 4)   Replications : 3

Table 3.3: Treatment combinations of incubation experiment

Treatments	**15 ºC (T_1)**	**25 ºC (T_2)**	**35 ºC (T_3)**	**45 ºC (T_4)**
Absolute control (S_1)	T_1S_1	T_2S_1	T_3S_1	T_4S_1
Soil + Rice husk (S_2)	T_1S_2	T_2S_2	T_3S_2	T_4S_2
Soil + Rice straw (S_3)	T_1S_3	T_2S_3	T_3S_3	T_4S_3
Soil + Vermicomposted rice husk (S_4)	T_1S_4	T_2S_4	T_3S_4	T_4S_4
Soil + Vermicomposted rice straw (S_5)	T_1S_5	T_2S_5	T_3S_5	T_4S_5
Soil + Rice husk biochar (S_6)	T_1S_6	T_2S_6	T_3S_6	T_4S_6
Soil + Rice straw biochar (S_7)	T_1S_7	T_2S_7	T_3S_7	T_4S_7
Soil + Farm yard manure (S_8)	T_1S_8	T_2S_8	T_3S_8	T_4S_8
Soil test based nutrient recommendation (S_9)	T_1S_9	T_2S_9	T_3S_9	T_4S_9

Plate 3.12: Soil sampling for incubation experiment

Separate portions of experimental soil (100g) was added with 0.2 g of rice husk, straw, vermicomposted husk, vermicomposted straw, rice husk biochar, rice straw biochar, and FYM. This was thoroughly mixed to avoid uneven decomposition. An unamended soil sample was taken in an incubation bottle and used as absolute control. In soil test based nutrient recommendation, whole nutrients were added during the start of incubation experiment based on soil test data (fertilizer recommendation for high yielding medium duration rice variety 'Uma' was 90:45:45 kg ha^{-1} N: P_2O_5: K_2O, test crop in third experiment). The characteristics of soil samples taken for incubation experiment are furnished in Table 3.4 and the quantity of fertilized added as per soil test data are given in Table 3.5. The characteristics of FYM used in incubation experiment are given in Table 3.6.

Soil samples in each bottle were wetted to field capacity moisture by adding distilled water. A vial containing 15 mL of 0.5N NaOH was placed inside the incubation bottle and the bottles were closed properly and kept in BOD incubators at different temperature *viz*., 15, 25, 35, and 45 °C for a period of 110 days (Plate 3.13).

3.2.1. Estimation of evolved CO_2 - C

The amount of CO_2 evolved was estimated using the procedure outlined by Anderson (1982) and the chemical reactions involved during incubation are detailed below.

$2NaOH + CO_2 \longrightarrow Na_2CO_3 + H_2O$ ……….Eq.1

$NaOH + HCl \longrightarrow 2NaCl + H_2O$ ………Eq.2

$Na_2CO_3 + BaCl_2 \longrightarrow BaCO_3 + 2NaCl$ ………Eq.3

$Na_2CO_3 + 2HCl \longrightarrow 2NaCl + H_2CO_3$ ……….Eq.4

CO_2 evolved during a given period of time was absorbed in a known volume and strength of NaOH. When CO_2 is absorbed in NaOH, it gets converted to Na_2CO_3 (eq. 1). The solution from the vial was transferred into conical flask, ensuring complete transfer from the vials with three washings. Prior to titration with 0.5N HCl, few drops of saturated $BaCl_2$ solution was added to precipitate the Na_2CO_3 as $BaCO_3$ (eq. 3), which otherwise would consume HCl (eq. 4) and underestimate the CO_2. Few drops of phenolphthalein indicator was added and titrated against 0.5N HCl. The end point was adjudged by the disappearance of pink colour.

Table 3.4: Characteristics of soil samples taken for incubation experiment

Characteristics	Value	Remarks
pH	5.36	Strongly acidic
EC (dS m^{-1})	0.06	Normal
Organic carbon (%) (g kg^{-1})	1.00 10.0	Medium
Nitrogen (kg ha^{-1})	286.30	Medium
Phosphorus (kg ha^{-1})	14.50	Medium
Potassium (kg ha^{-1})	231.28	Medium
Calcium (mg kg^{-1})	104.30	Deficient
Magnesium (mg kg^{-1})	29.70	Deficient
Sulphur (mg kg^{-1})	3.10	Deficient
Iron (mg kg^{-1})	147.80	Sufficient
Manganese (mg kg^{-1})	18.10	Sufficient
Zinc (mg kg^{-1})	4.20	Sufficient
Copper (mg kg^{-1})	3.52	Sufficient
Boron (mg kg^{-1})	0.38	Deficient

Table 3.5: Quantity of fertilizer applied as per soil test data

Nutrients	Soil test based nutrient recommendation
Nitrogen	91 % N (Urea and Factamphos)
Phosphorus	83 % P_2O_5 (Factamphos)
Potassium	71 % K_2O (Muriate of potash)
Calcium	350 kg $CaCO_3$ ha^{-1}
Magnesium	80 kg $MgSO_4$ ha^{-1}
Sulphur	25 kg S ha^{-1} (Factamphos and $MgSO_4$)
Boron	10 kg borax ha^{-1}

Table 3.6: Characteristics of farm yard manure (FYM)

Parameters		Values
Moisture (%)		12.06
Bulk density (Mg m^{-3})		0.32
pH		7.71
EC (dS m^{-1})		1.68
C	%	22.28
N		1.58
P		0.82
K		0.67
Ca		1.286
Mg		0.495
S		0.385
Fe	mg kg^{-1}	448.0
Mn		66.98
Cu		12.5
Zn		38.57
B		4.30
C/N ratio		14.10

Plate 3.13: View of BOD incubators

The amount of CO_2 released from the samples were determined using the following formula

$$\mathbf{mg\ CO_2 = (B\text{-}V) \times (N \times E)}$$

B = Volume of standard HCl used to titrate the blank

V = Volume of standard acid needed to titrate the trapped solution of samples to the end point

N = Normality of HCl

E = Equivalent weight of C in CO_2

(1 ml, 1N NaOH ≡ 22 mg CO_2 or 6 mg CO_2 –C)

E = 6 (if data are expressed as C (*i.e.*, mg CO_2 –C)

E = 22 (if data are expressed as CO_2 (*i.e.*, mg CO_2)

The evolved CO_2 –C was estimated at specific time intervals (daily during the first seven days and every alternate day upto 21 days and at five days interval thereafter for a period of 110 days) of incubation. On each sampling event, the vials were replaced with another set of vials containing fresh NaOH and bottles were kept back in the incubator. Soil moisture was checked at each sampling time by weighing the bottles and was adjusted if required, with distilled water.

3.2.2. Determination of carbon mineralization

First order kinetic equations were used to determine the carbon mineralization:

$$\mathbf{A_t = A_0e^{-kt}}$$

k= First order rate constant (day^{-1})

A_0 and A_t are the amounts of carbon at zero and 't' time.

3.2.3. Thermal sensitivity parameters

3.2.3.1. Q_{10}

Q_{10} indicates the responses of biological processes with temperature. Q_{10} values were calculated as a function:

$$\mathbf{Q_{10} = (k_2/\ k_1)^{(10/T_2 - T_1)}}$$

k_2 and k_1 are the reaction rates at temperatures T_2 and T_1, respectively (Kirschbaum 1995).

3.2.3.2. Activation energy

The activation energy (Ea) was calculated using Arrhenius equation:

$$\mathbf{k = A \exp(-Ea/RT)}$$

k = Decomposition rate constant
A = Frequency factor
Ea = Activation energy (kJ mol^{-1})
R= 8.314 J K^{-1} mol^{-1}
T= Temperature (K)

Ea was calculated from the slope (Ea/R) obtained by plotting ln k against 1/T (Knorr *et al.*, 2005).

3.2.4. Dehydrogenase activity

The dehydrogenase activity was determined as per the procedure explained by Casida *et al.* (1964) before and after the incubation. For that, 1g of soil was weighed into an air tight screw capped test tube of 15 mL capacity, to which 0.2 mL of 3 per cent triphenyl tetrazolium chloride solution was added. Then, 0.5 mL of 1 per cent glucose solution was added into each tube. Gently tapped the bottom of the tube to drive out the trapped oxygen fully there by forming a water seal above the soil thus ensuring freedom from air bubbles. Tubes were then incubated at 28±0.5 °C for 24 h. After incubation, 10 mL methanol was added and the contents were vigorously shaken. Samples were allowed to stand for six hours and the intensity of pink colour was read in spectrophotometer at a wavelength of 485 nm.

3.2.5. Microbial enumeration

The quantitative assay of soil microflora was carried out by serial dilution plate technique. Ten gram of soil sample was added to 90 mL sterile water contained in 250 mL conical flask and shaken for 30 minutes in an orbital shaker. One millilitre of this solution was then transferred to a test tube containing nine millilitre sterile water to obtain 10^{-2} dilution. From which further dilutions *viz.*, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6} and 10^{-7} were prepared using the serial dilution technique. For enumeration of fungi, bacteria and actinomycetes from the soil, rose bengal agar, nutrient agar and kenknight's medium were respectively used. The composition of media are given in Table 3.7.

a) Estimation of bacterial population

Bacterial population was estimated using 10^{-6} dilution in nutrient agar medium. The dishes were incubated at room temperature for 48 hours. The bacterial colonies developed were counted and expressed as number of colony forming unit (cfu) per gram of soil.

b) Estimation of actinomycetes population

Population of actinomycetes was estimated using 10^{-3} dilution in Kenknight's medium. The dishes were incubated at room temperature for 7 days. The colonies developed were counted and expressed as number of colony forming unit (cfu) per gram of soil.

c) Estimation of fungal population

One millilitre from 10^{-4} soil dilution was pipetted into petri dishes to which 20 mL melted and cooled Rose Bengal agar medium was poured. Petri dishes were then swirled thoroughly to get uniform distribution. After solidification, the petri dishes were incubated at room temperature for 3-4 days. The fungal colonies developed were counted from which population of fungi in one gram of soil was calculated and expressed as number of colony forming unit (cfu) per gram of soil.

3.2.6. Carbon fractions

Fractionation of carbon in soil samples drawn from incubation bottle before and after the experiment were also done. The procedure for the extraction and determination of carbon fractions are presented below.

3.2.6.1. Water soluble and Hot water-extractable carbon

Water soluble carbon (WSC) and hot water-extractable carbon (HWEC) were determined by following the procedure (Figure 3.1) described by Ghani *et al.* (2003). Field moist soil samples were weighed into a 100 mL polypropylene centrifuge tubes and were extracted with 30 mL distilled water for one hour on an end-over-end shaker and centrifuged for half an hour at 10000 rpm.

Table 3.7: Media composition for serial dilution plate technique

Microorganisms assayed	**Name of the growth media**	**Media composition**	**Reference**
Bacteria	Nutrient agar medium	Peptone : 5 g Beef extract : 1 g NaCl : 5 g Agar : 20 g Distilled water : 1 L pH : 6.5-7	Lapage *et al*., 1970
Actinomycetes	Kenknights medium	Dextrose : 1 g KH_2PO_4 : 1 g $MgSO_4$: 0.1 g KCl : 0.1 g $NaNO_3$: 0.1 g Agar : 20 g Distilled water : 1 L pH : 7	Rao, 1977
Fungi	Rose Bengal agar medium	Dextrose : 10 g Peptone : 5 g KH_2PO_4 : 1 g $MgSO_4$: 0.5 g Agar : 20 g Rose Bengal : 0.03 g Streptomycin : 30 mg Distilled water : 1 L	Martin, 1950

The supernatant was filtered and the extract was estimated for water soluble fraction. From the extracted supernatant 5 mL was pipetted into a conical flask and treated with 5 mL of $K_2Cr_2O_7$ (0.07N), 10 mL H_2SO_4 (concentrated) and 5 mL of H_3PO_4. This sample was mixed carefully and digested at 100 °C for half an hour using a hot plate. After half an hour, the contents were cooled by adding 200 mL distilled water and titrated against 0.035 N ferrous ammonium sulphate ($(NH_4)_2Fe(SO_4)_2.6H_2O$) using diphenylamine ($C_{12}H_{11}N$) as the indicator. This fraction of carbon was classified as water soluble carbon (WSC).

Further 30 mL of distilled water was added to the sediments in the same centrifuge tubes and shaken on a rotary shaker for one minute to suspend the soil in water. The tubes were capped and left for 16 hours in a water bath at 80 °C. At the end of extraction, tubes were shaken to ensure that hot water-extractable carbon released from the soil organic matter was fully suspended in the extraction medium. These tubes were centrifuged for 30 minutes at 10000 rpm. The supernatant was filtered and the carbon content of the extract was determined as in the case of WSC and classified as 'hot water- extractable carbon'(HWEC).

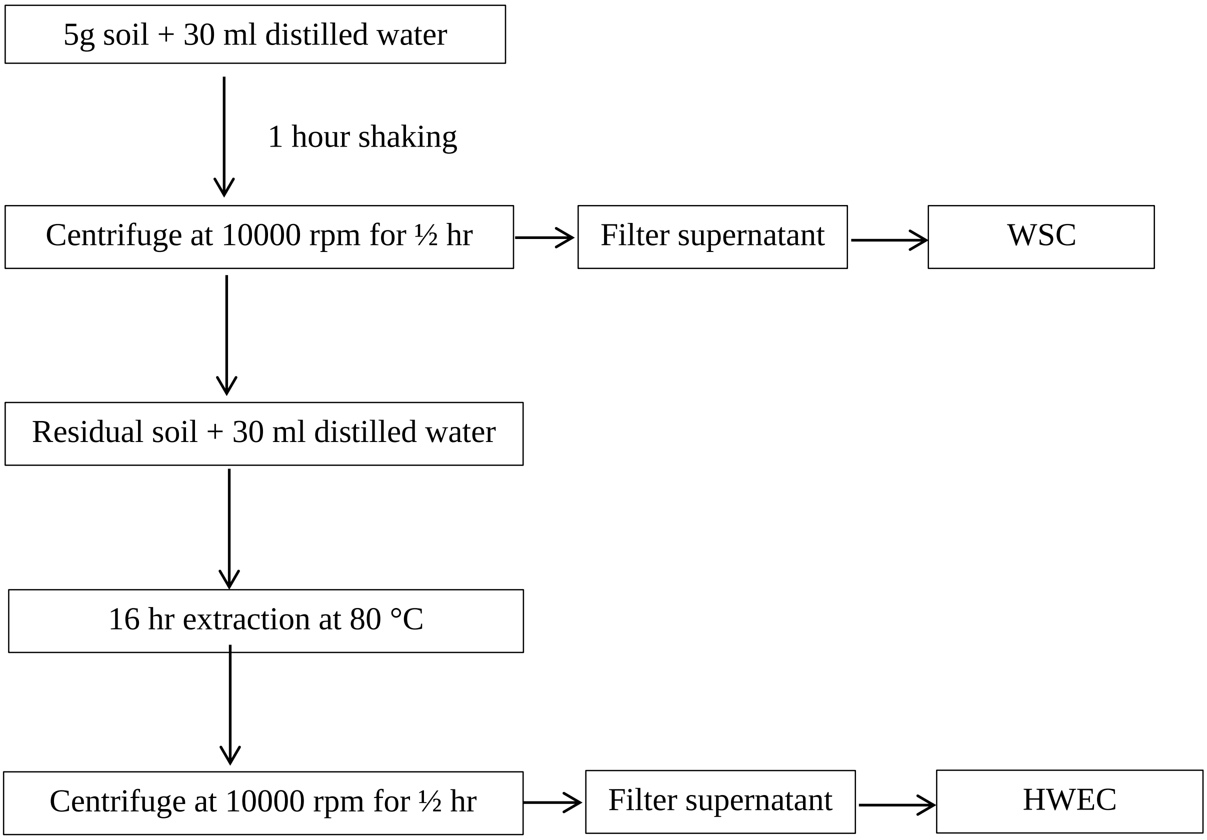
3.2.6.2. Permanganate oxidizable carbon

Permanganate oxidizable carbon (POXC) was determined by following the procedure outlined by Blair *et al*. (1995). Soil samples were taken in centrifuge tube and oxidized with 25 mL of 333 mM $KMnO_4$ by shaking in mechanical shaker for one hour. The tubes were centrifuged at 4000 rpm for five minutes and 0.1 mL of supernatant solution was diluted to 25 mL with double distilled water. The concentration of $KMnO_4$ was measured at 565 nm using spectrophotometer. The change in concentration of $KMnO_4$ was used to estimate the amount of organic carbon oxidized, assuming that 1.0 mM MnO_4 of was consumed in the oxidation of 0.75 mM (9.0 mg) of carbon.

3.2.6.3. Total carbon

Total carbon content in the samples were estimated by CHNS analyzer (Model: Elementar's vario EL cube).

Fig. 3.1: Flow chart of extracting water soluble carbon (WSC) and hot water extractable carbon (HWEC)



3.2.6.4. Microbial biomass carbon

Microbial biomass carbon (MBC) was determined by chloroform fumigation extraction method as described by Jenkinson and Powlson (1976). For each sample, three sets of 10 g soil was weighed, of which one was used to determine the moisture content of the soil, another for immediate extraction with 0.5 M K_2SO_4 and the third one for fumigation. In order to fumigate, ethanol free chloroform (distilled chloroform) was kept in 250 mL porcelain dishes placed at the bottom portion of a vacuum desiccator. Few glass beads were kept in the dishes to reduce the bumping. A beaker containing sample was placed in the vacuum desiccator, the inner surface of which was lined with moist filter paper. Vacuum pump was connected to the desiccator until the chloroform boiled. The outlet of desiccator was closed and was kept in darkness overnight at 25 °C. On the next day, filter paper lining and chloroform containing porcelain dishes were removed after releasing the vacuum. Fumigated samples were extracted with 25 mL of 0.5 M K_2SO_4 for 30 minutes and filtered.

The supernatant collected for fumigated and non- fumigated samples were estimated for their carbon content. For this, 10 mL of the supernatant was transferred into 500 mL conical flasks and added with the reagents 2 mL $K_2Cr_2O_7$ (0.2N), 10 mL H_2SO_4 (concentrated) and 5 mL H_3PO_4. The flasks were kept on hot plate at 100 °C for half an hour under reflux. 200 mL distilled water was added into the conical flask in order to stop the reaction. After cooling, diphenylamine indicator ($C_{12}H_{11}N$) was added and titrated against ferrous ammonium sulphate (0.05N). Microbial biomass carbon in the soil was calculated using the following formula.

$$\mathbf{MBC\ (\mu g\ g^{-1}\ soil) = \frac{EC_F - EC_{UF}}{K_{EC}}}$$

(EC_F and EC_{UF} were extractable carbon in the fumigated and un-fumigated samples, respectively)

$$K_{EC} = 0.25 \pm 0.05$$

(K: Efficiency of extraction of microbial biomass carbon)

3.3. FIELD EXPERIMENT

A field experiment to evaluate the efficacy of rice residues and their products in lowland rice was conducted at ARS Mannuthy, Thrissur district. The field is located in the Agro-ecological unit (AEU) - 10 (North central laterites) of Kerala.

3.3.1. Details of field experiment

Field experiment was formulated with nine treatments replicated thrice and laid out as RBD. The layouts of field experiment are given in Figure 3.2. The treatment details of field experiment are given in Table 3.8.

The meteorological data recorded during field experiment are furnished in Table 3.9.

3.3.1.1. Variety

Uma (MO 16), the red kernelled medium bold type with 115-120 days duration possessing a post-harvest dormancy of three weeks, resistant to BPH and GM bold biotype-5 and non-lodging nature, which forms one of the most popular red rice in Kerala served as the test crop. The seeds were purchased from Agricultural Research Station, Mannuthy

Seeds were soaked for 12 hours in a solution of *Pseudomonas fluorescenes* at the rate of 10 g per litre of water per kg of seed. Pre-germinated rice seeds were sown on the very next day on a mat nursery filled with moist farm soil (Plate 3.14).

3.3.1.2. Land preparation

The experimental field was ploughed very well to obtain a good tilth and transformed into small plots of 5m x 4m size surrounded by bunds of 30cm width and height (Plate 3.15), leaving sufficient space for irrigation and drainage channels in between the plots.

3.3.1.3. Application of lime, manures, and fertilizers

Lime was applied (Plate 3.16) to all the plots except absolute control. Lime was added @ 600 kg ha^{-1} in T_2 (Adhoc KAU organic POP) in two splits, the first one as basal dressing at the time of first ploughing followed by a top dressing one month after transplanting (KAU, 2017).

Table 3.8. Treatment details of field experiment

Treatments	Descriptions
T_1	Absolute Control
T_2	Adhoc KAU organic POP
T_3	Soil test based nutrient recommendation + FYM @ 5t ha^{-1}
T_4	Soil test based nutrient recommendation + Vermicomposted rice husk @ 5t ha^{-1}
T_5	Soil test based nutrient recommendation + Vermicomposted rice straw@ 5t ha^{-1}
T_6	Soil test based nutrient recommendation + Rice husk biochar @ 5t ha^{-1}
T_7	Soil test based nutrient recommendation + Rice straw biochar @ 5t ha^{-1}
T_8	Soil test based nutrient recommendation + Rice husk @ 5t ha^{-1}
T_9	Soil test based nutrient recommendation + Rice straw @ 5t ha^{-1}

Table 3.9: Meteorological data during field experiment in 2019

Month	Temperature (°C)		Relative humidity (%)	Rainfall (mm)
	Max.	Min.		
June	32.2	23.5	83	324.4
July	30.4	22.8	85	654.4
August	29.5	21.9	89	977.5
September	31.2	22.0	85	419.0
October	32.4	21.4	79	418.4
November	32.9	21.7	71	205.0

Fig. 3.2: Layout of the experimental field

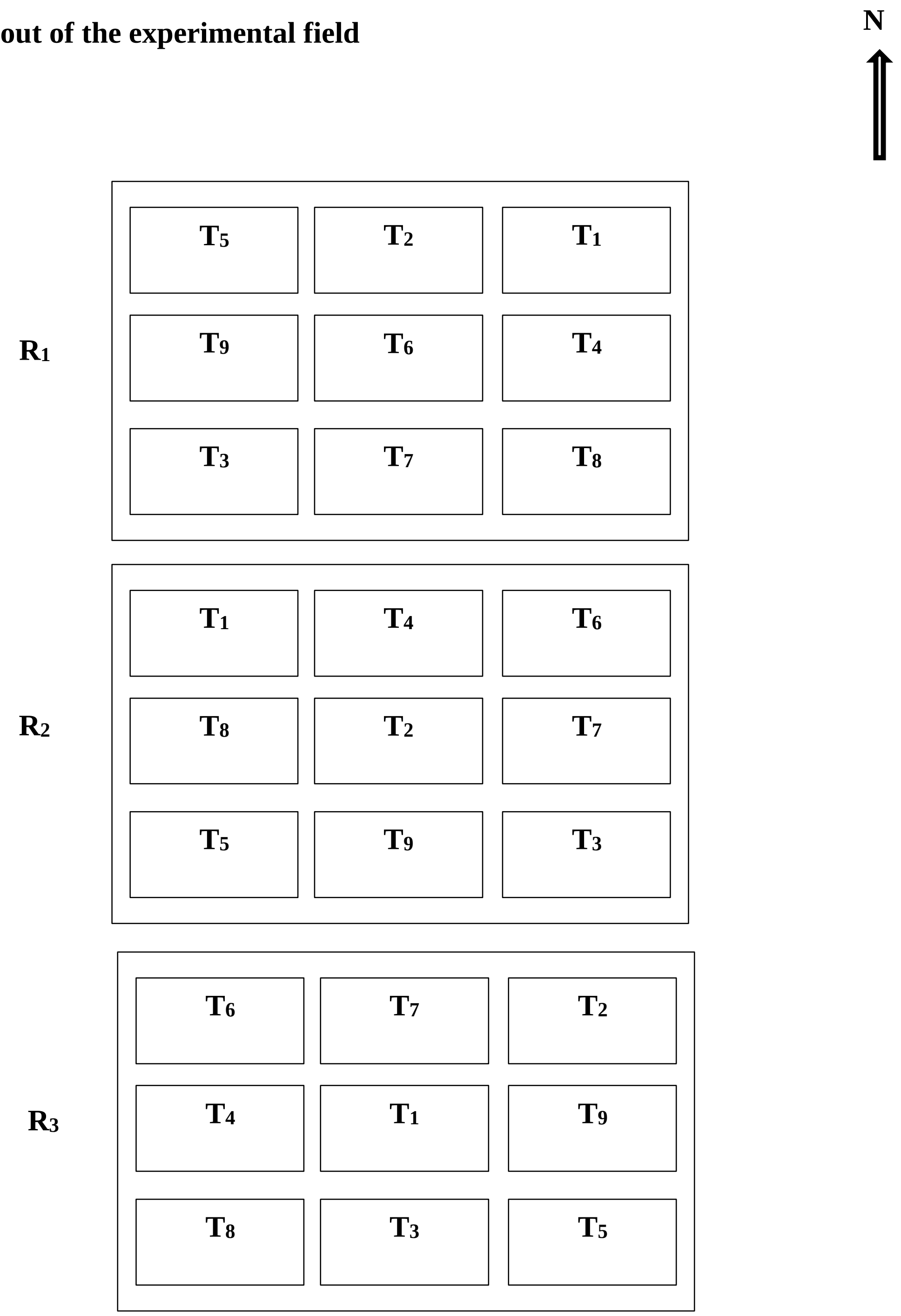


Plate 3.14: Mat nursery

Plate 3.15: Land preparation

Plate 3.16: Application of lime

Plate 3.17: Application of residues and their products

Plate 3.18: Transplanting

It was applied based on soil test data as $CaCO_3$ @ 350 kg ha^{-1} in plots receiving the treatments T_3 to T_9. The first dose was given basally at the time of field preparation and second as top dressing one month after transplanting.

Five tonnes of FYM was applied full as basal and 600 to 800 kg neem cake ha^{-1}(half as basal and second half as top dressing at active tillering stage) were applied in T_2 (Adhoc KAU organic POP). In T_3 (Soil test based nutrient recommendation + FYM), farm yard manure was applied @ 5 tonnes ha^{-1} as per package of practices recommendations (KAU, 2016) a fortnight after lime application. Vermicomposted rice husk, vermicomposted rice straw, rice husk biochar, rice straw biochar, rice husk, and rice straw were applied at the rate of 5 tonnes ha^{-1} a fortnight after lime application and are thoroughly incorporated into the soil (Plate 3.17).

Fertilizers were given as per the package of practices recommendations of KAU modified based on soil test results (Table 3.5). Full dose of phosphorus and half of required doses of nitrogen and potassium were supplied as basal dose, and was added to the field four days after transplanting. The top dressing of fertilizers (half dose of nitrogen and potassium) was done seven days before panicle initiation stage of the crop.

3.3.1.4. Transplanting

Seedlings, 18 days old were transplanted at a spacing of 20 cm x 15 cm @ 2-3 seedlings per hill (Plate 3.18).

3.3.1.5. Water management

Water level was maintained at about 1.5 cm during transplanting and was gradually increased to 5 cm until maximum tillering stage (Plate 3.19). Adequate amount of water was maintained at grain filling stage (Plate 3.20). Two weeks prior to harvest the field was completely drained.

3.3.1.6. Weed management

Hand weeding was done at 25 DAT (Days after transplanting).

3.3.1.7. Plant protection

According to the requirement, plant protection measures were carried out as per the Package of Practices Recommendations (KAU, 2016).

3.3.1.8. Harvesting

After 110 days, the crop was harvested (Plate 3.21) plot wise, threshed (Plate 3.22) and data on yield and other observations were recorded separately.

3.3.2. Observations recorded

3.3.2.1. Monitoring Eh and pH

The Eh (redox potential) and pH of the experimental site was measured at weekly intervals immediately after transplanting till the harvest of the crop. The redox potential of the experiment site was recorded using a redox meter (model: RM 1K TOA). This was done by installing a redox electrode in the field at a depth of 10 cm. Soil pH was monitored using pH meter (Eutech –model: pHtestr 30).

3.3.2.2. Soil analysis

Soil samples collected before and after the rice were analysed for physical and chemical characteristics. The procedures adopted for the characterisation of soil samples are detailed in Table 3.10.

3.3.2.3. Fractionation

Fractions of the nutrient elements *viz*., carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, and silicon were studied before planting, at tillering, and panicle initiation stages.

3.3.2.3.1. Fractionation of carbon

Fractions of soil carbon *viz*., Water soluble carbon (WSC), hot water-extractable carbon (HWEC), permanganate oxidizable carbon (POXC), total carbon (TC), and microbial biomass carbon (MBC) were studied and the procedures followed are outlined in section 3.2.6.

3.3.2.3.2. Fractionation of nitrogen

Fractionation of nitrogen in soil samples drawn from each plot were also done at three stages *viz*., before planting, at tillering, and panicle initiation. The organic nitrogen fractions included total hydrolysable nitrogen and amino acid nitrogen whereas the inorganic fractions comprised of ammoniacal and nitrate nitrogen.

Table 3.10: Methods of soil analysis

Characteristics	Methods	References
Physical properties		
Bulk density	Keen-Raczkowski brass cup method	Piper, 1942
Particle density		
Porosity		
Water holding capacity		
Mean weight diameter	Yoder's apparatus	Yoder (1936) as cited by Pal, 2013
Chemical properties		
Organic carbon	Wet oxidation method	Walkley and Black, 1934
Available N	Alkaline permanganometry	Subbiah and Asija, 1956
Available P	Extracted with Bray No.1 and estimated colorimetrically by reduced molybdate ascorbic acid blue colour method using Spectrophotometer (Model: Lambda 25)	Bray and Kurtz, 1945
Available K	Extracted with neutral normal ammonium acetate and estimated using Flame photometer (Model:CL 308)	Jackson, 1958
Available Ca	Extracted with neutral normal ammonium acetate and estimated using ICP OES (Model: Optima® 8x00 series)	
Available Mg		
Available S	Extracted with 0.15 % $CaCl_2$ and estimated turbidometrically using Spectrophotometer (Model: Lambda 25)	Williams and Steinberg, 1959
Available micronutrients (Fe, Mn, Cu, and Zn)	Extracted with 0.1 M HCl and estimation using ICP OES (Model: Optima® 8x00 series)	Sims and Johnson, 1991
Available B	Extracted with hot water and estimated colorimetrically by Azomethine-H using spectrophotometer (Model: Lambda 25)	Berger and Truog, 1939; Gupta, 1972
Available Si	Extracted with 0.5M acetic acid and estimated colorimetrically by ANSA using spectrophotometer (Model: Lambda 25)	Korndorfer *et al.*, 2001

Plate 3.19: Tillering stage

Plate 3.20: Grain filling stage

Plate 3.21: Harvesting

Plate 3.22: Threshing

1) Organic fractions of nitrogen (Stevenson, 1996)

i) Preparation of hydrolysate

Preparation of hydrolysate is a prerequisite for the determination of organic forms of nitrogen in soil. Five gram of soil sample was transferred into a 1000 mL round bottom flask, added 2 drops of octyl alcohol and 20 mL of HCl (6N) and boiled it gently under reflux for 12 hours using heating mantle. After completion of hydrolysis, washed the reflux condenser with distilled water, cooled and filtered the hydrolysis mixture. The pH of the extract was adjusted to 5.0 by dropwise addition and constant stirring with NaOH (5N) and finally pH was adjusted to 6.5 ± 0.1 with NaOH (0.5 N). The neutralized extract was transferred to a 100 ml volumetric flask and made to volume with distilled water.

ii) Analysis of hydrolysate

Determination of total hydrolysable nitrogen

Five ml of the above neutralized extract was digested with 0.5 g of K_2SO_4-$CuSO_4$ digestion mixture and 2 mL of H_2SO_4 (concentrated) in a 100 mL Kjeldahl digestion flask continuously for one hour. The digested material was cooled and distilled under alkaline conditions using 10 mL of NaOH (10 N). The distillate was absorbed in 5 mL of boric acid containing double indicator (2 %) and titrated with standard H_2SO_4 (0.02 N).

Determination of amino acid nitrogen

Five mL of the above neutralized hydrolysate was taken in a 50 mL distillation flask. One milliliters of NaOH (0.5N) was added and the content of the flask was heated in water bath at100 °C until the volume of the same reduced to half. After cooling, 500 mg of citric acid and 100 mg of ninhydrin were added to the flask and kept immersed in a water bath at 100 °C. After one minute, the flask was swirled for a few seconds, without removing it from water bath and then allowed to remain in the water bath for additional 9 minutes. The flask was then connected to the distillation set and the amount of NH_3 liberated by steam distillation was determined as mentioned above.

2) Inorganic fractions of nitrogen

Inorganic forms of nitrogen in the soil include exchangeable NH_4 and NO_3, which were extracted with 2N KCl (Keeney and Nelson, 1982)

Ammoniacal nitrogen

The soil samples were extracted with 2 N KCl in a 1:10 soil to KCl ratio by shaking for one hour and filtered off using Whatman No.1 filter paper. A known quantity of extract was pipetted into distillation flask, added with a pinch of freshly ignited MgO and the evolved nitrogen was collected in boric acid containing double indicator and titrated against standard acid. This fraction of nitrogen was classified as ammoniacal nitrogen.

Nitrate nitrogen

Further distillation of the above was done with Devarda's alloy. To the same extract in distillation tube, a pinch of devardas alloy (alloy of aluminium, copper, and zinc), 10 mL of 1 per cent NaOH was added and the evolved nitrogen was trapped in boric acid containing double indicator and titrated against standard acid. This fraction of nitrogen was classified as nitrate nitrogen.

3.3.2.3.3. Fractionation of phosphorus

Inorganic and organic phosphorus are the major phosphorus fractions in soil.

Inorganic fractions

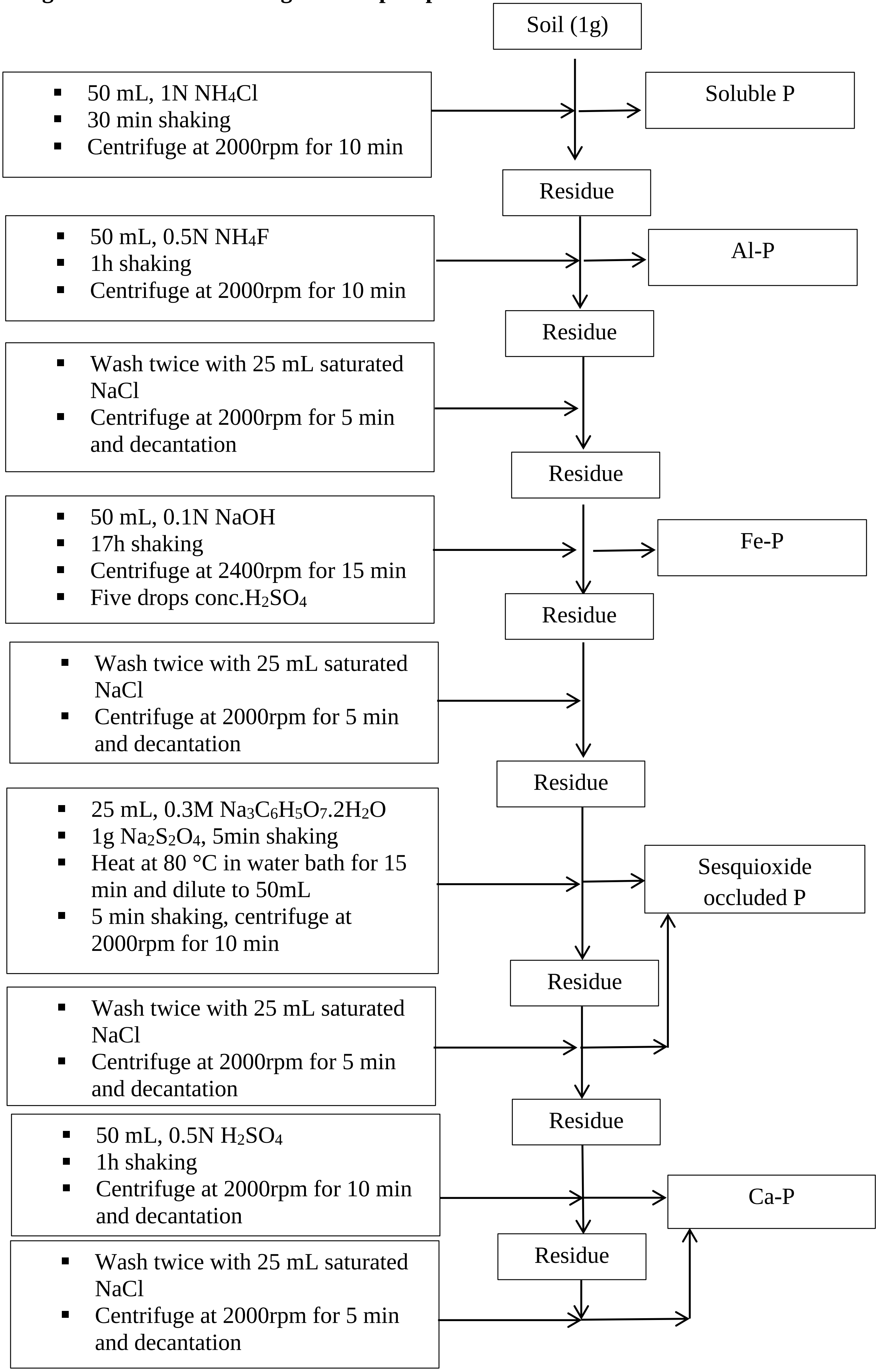
Inorganic fractions of soil phosphorus *viz*., soluble phosphorus (Soluble-P), aluminium bound phosphorus (Al- P), iron bound phosphorus (Fe-P), Sesquioxide occluded P, and calcium bound phosphorus (Ca-P) were extracted by the method proposed by Peterson and Corey (1966). The flow chart for the extraction of inorganic phosphorus fractionation is depicted in Figure 3.3.

Extraction of soil inorganic phosphorus fractions

Soluble-P

One gram soil was taken in a 100 mL polypropylene centrifuge tube. To this 50 mL of 1N NH_4Cl solution was added and shaken for 30 minutes to remove the easily soluble and

Fig.3.3. Flow chart of inorganic soil phosphorus fractionation



loosely bound phosphorus. The extract was then centrifuged at 2000rpm for 10 minutes. The supernatant solution was taken for soluble-P estimation.

Al-P

The soil residue in the centrifuge tube was added with 50 mL of 0.5N NH_4F and shaken for one hour. Then the tube was centrifuged for 10 minutes at 2000 rpm. Filtered the supernatant through 0.5g activated charcoal and it was taken for the estimation of Al-P.

Fe-P

The residual soil was washed twice with 25 mL of saturated NaCl and centrifuged at 2000 rpm for 5 minutes and decanted the solution. Then, soil residue in the centrifuge tube was added with 50 mL of 0.1N NaOH and shaken for 17 hours. The suspension was centrifuged for 15 min at 2400 rpm. To this five drops of concentrated H_2SO_4 was added and the flask was swirled for the flocculation of organic matter. Centrifuged the extract and filtered the supernatant through 0.5g activated charcoal and it was taken for the estimation of Fe-P.

Sesquioxide occluded-P

The residue was again washed twice with 25 mL saturated NaCl and centrifuged at 2000 rpm for 5 minutes and decanted .To the soil residue, 25 mL of 0.3M $Na_3C_6H_5O_7.2H_2O$ and one gram $Na_2S_2O_4$ were added and shaken for 5 minutes. After that the solution was treated in a water bath at 80 °C. The solution was diluted into 50 mL and shaken for 5 minutes and centrifuged at 2000 rpm for 10 minutes. The solution was decanted into another flask after centrifugation. The residue was washed with 25 mL of saturated NaCl. This was centrifuged at 2000 rpm for 5 minutes and decanted the supernatant solution to the above flask. This extract was used for the estimation of sesquioxide occluded-P.

Ca-P

To the soil residue, 50 mL of 0.5 N H_2SO_4 was added and shaken for 1 hour on a shaker. The solution was centrifuged at 2000 rpm for 10 minutes and decanted into another flask. The soil residue was washed twice with 25 mL of saturated NaCl, centrifuged (2000 rpm for 5 minutes) and decanted. This extract was taken for the estimation of Ca-P.

Estimation of inorganic phosphorus fractions

Soluble and Ca-P

Five mL of each of the extract was pipetted out into a 50 mL volumetric flask and distilled water was added to increase the volume upto 20 mL. To this, 4 mL of reagent B (ascorbic acid in ammonium molybdate and potassium antimony tartarate with 5 N H_2SO_4) was added. The volume was made upto 50 mL and the absorbance was read at 660nm.

Al-P

Five mL of the extract was pipetted out into a 50 mL volumetric flask and to this 7.5 mL of 0.8 M boric acid was added. Then reagent B was added as same as in soluble and calcium bound phosphorus fractions. The intensity of blue colour was read in spectrophotometer at 660nm.

Fe-P and sesquioxide occluded-P

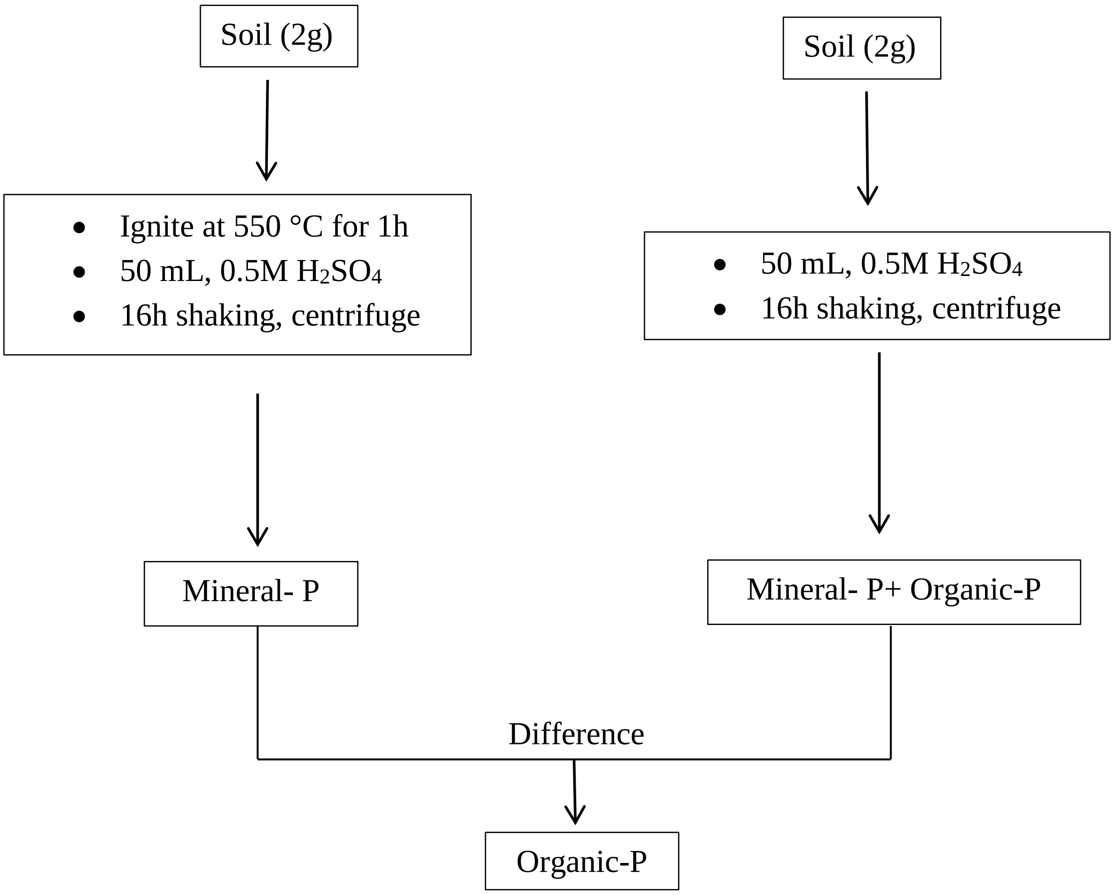
Five mL of the extract was pipetted and the solution pH was adjusted using 2M HCl in the presence of p-nitrophenol (0.25 %). For this, a separate 5 mL of aliquot was pipetted out to which two drops of 0.25 per cent p-nitrophenol was added and 2M HCl was taken in a burette and added drop by drop till the colour changed from yellow to colourless. This estimated amount of 2M HCl was added to the aliquot taken for the estimation of iron bound and sesquioxide occluded phosphorus.

Organic phosphorus

The organic phosphorus fraction present in the soil samples were estimated by ignition method (Figure 3.4) described by Saunders and Williams (1955).

Two grams soil sample was ignited in a muffle furnace at a temperature of 550 °C for one hour and transferred it into a 100 mL centrifuge tube. Two grams of fresh (unignited) sample was taken in another 100 mL centrifuge tube. 50 mL of 0.5M H_2SO_4 was added to each centrifuge tube and shaken for 16 hours. The extract was centrifuged and 10 mL aliquot was transferred into 50 mL volumetric flask. To this, five drops of p-nitrophenol indicator was added and adjusted the pH to 5.0 with 5M NaOH (until the colour just changes from colourless to yellow) and the aliquot was taken for the estimation of organic phosphorus.

Fig. 3.4. Flow chart of soil organic phosphorus fractionation



Organic phosphorus was obtained by subtracting the phosphorus content in the ignited sample from unignited sample.

3.3.2.3.4. Fractionation of potassium

Water soluble exchangeable and exchangeable potassium in the soil samples was estimated and the procedure adopted for estimation are given below.

Water soluble potassium

Five gram soil samples were weighed into 100ml conical flask and to this, 25 mL of distilled water was added and shaken for 5 minutes on a mechanical shaker. The extract was filtered and the concentration of water soluble potassium was determined using flame photometer (USSLS, 1954).

Exchangeable potassium

Exchangeable potassium in the soil samples was obtained by subtracting water soluble potassium from available potassium.

Available potassium content in the sample was found out by employing the method suggested by Hanway and Heidel (1952). For that, five gram soil samples were taken in a 100 mL conical flask and 25 mL of neutral normal ammonium acetate was added. The contents were shaken for five minutes on a mechanical shaker and filtrate was used for the determination of available K.

Exchangeable K= Available K - Water soluble K

3.3.2.3.5. Fractionation of calcium and magnesium

Water soluble fraction

Water soluble fraction was estimated by the modified procedure of Baruah *et al.* (2011) where five grams of soil sample with 25 mL deionized water was centrifuged at 4000 rpm for 30 minutes, decanted and the residue was rinsed with 25 mL of deionized water followed by shaking, centrifugation and filtration.

Exchangeable fraction

Exchangeable fraction of calcium and magnesium was done as per the procedure outlined by Mokwunye and Melsted (1972).

Exchangeable fraction was extracted by shaking 1g of soil sample with 20 mL of neutral normal ammonium acetate for 45 minutes followed by centrifuging for 10 minutes at 2000 rpm and decanting the supernatant. Additional 20 mL aliquots of ammonium acetate were used with 10 minutes shaking periods followed by centrifuging until a total of 100 mL of the supernatant solution was collected.

The different fractions of Ca and Mg were analyzed using ICP-OES (PerkinElmer – model: Optima® 8x00 series).

3.3.2.3.6. Fractionation of sulphur

The inorganic or available sulphur as well as organic sulphur fractions were estimated and the detailed procedures are given below.

Inorganic sulphur

Soil samples were extracted with 0.15 per cent $CaCl_2$ in the ratio of 1:5. The sulphate sulphur in the soil extract was determined by developing the turbidity in the presence of barium sulphate and sodium acetate-acetic acid buffer (Chesnin and Yien, 1950).

Organic sulphur

Organic sulphur fraction was estimated by following the procedure described by Sankhyan *et al*. (2015). The sulphate sulphur or inorganic sulphur fraction was substracted from the total sulphur fraction. The total sulphur in the soil samples were estimated using CHNS analyser (Model: Elementar’s vario EL cube).

3.3.2.3.7. Fractionation of silicon

Fractions of silicon were determined using the procedure described by Georgiadis *et al*. (2013) and are depicted in Figure 3.5.

Mobile silicon (Si_m)

Soil samples were extracted with 0.01M $CaCl_2$ in the ratio of 1:5 for 24h on an end-over end horizontal shaker. The samples were shaken at the rate of $1minh^{-1}$ (to avoid abrasion from mineral grains) at 150 rpm. After extraction, the samples were centrifuged at 3000 rpm for 5 min and the supernatant was filtered. The concentration of silicon was estimated using ICP-OES.

Adsorbed silicon (Si_{ad})

The residual soil was extracted with 0.01M CH_3COOH in the ratio of 1:10. After the first step, the samples were rinsed with distilled water for the complete removal of dissolved silicon. Then, 10 mL of the extract was added to each sample. The samples were then shaken for 24 h and the filtrate was used for the estimation of adsorbed silicon using ICP-OES.

Organic silicon (Si_{org})

The residual soil was treated with 20 mL of 17.5 per cent H_2O_2 and kept for 1h at room temperature. Then, 10 mL of 35 per cent H_2O_2 was added and the samples were kept in a water bath at 85° C for 7 h. After cooling, it was centrifuged at 3000 rpm for 15 min and the extract was filtered. The silicon content was estimated using ICP-OES.

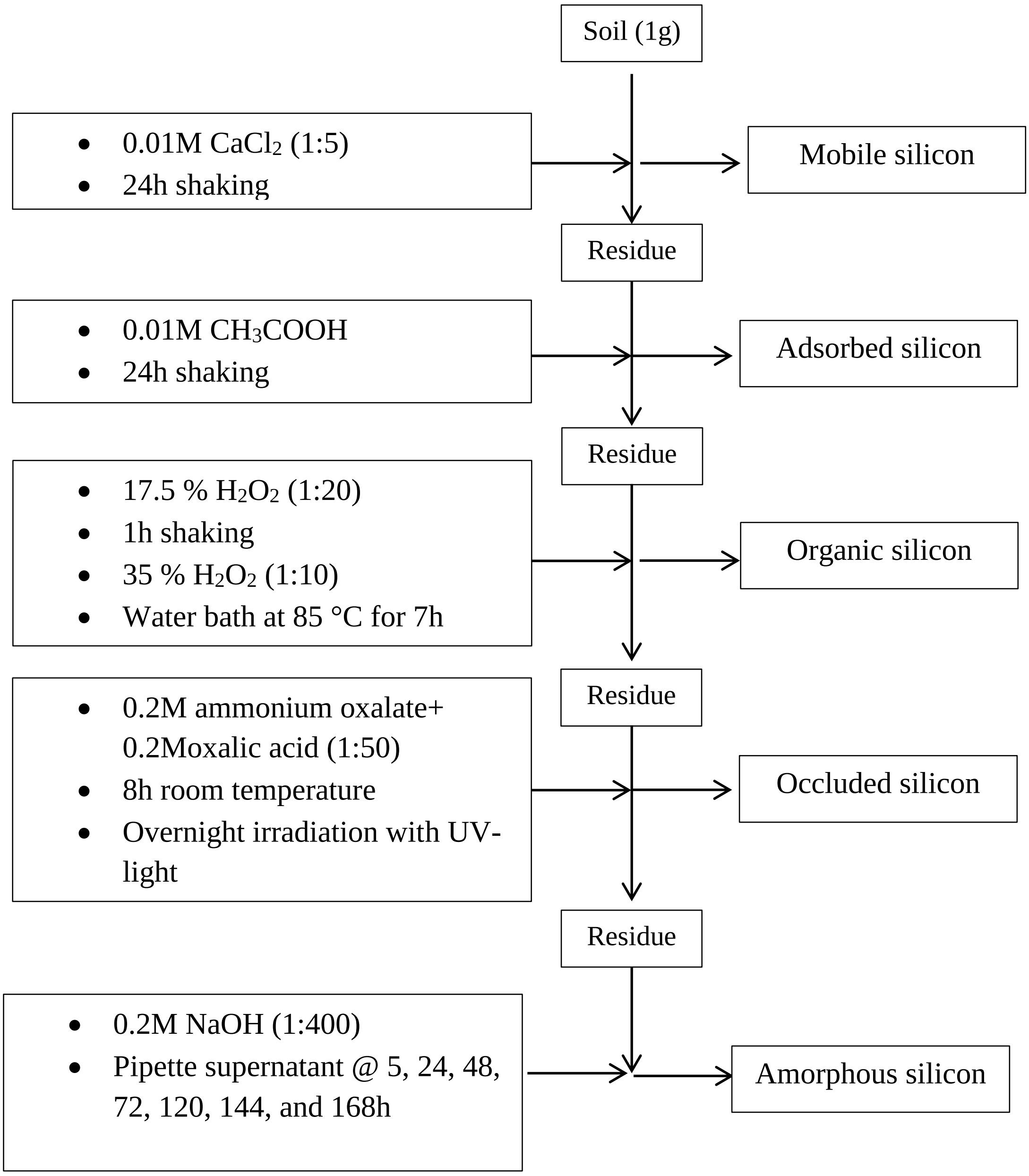
Occluded silicon (Si_{occ})

The residual soil was extracted with 0.2M ammonium oxalate and 0.2M oxalic acid under UV-light. The extract was applied at daylight and room temperature for 8h using a soil to solution ratio of 1:50. Then, the supernatant was irradiated with UV- light for overnight. During the whole time, the samples were shaken horizontally for $1minh^{-1}$. After shaking, it was filtered and silicon was estimated using ICP-OES.

Amorphous silicon (Si_{amr})

The residual soil was treated with 0.2M NaOH using a sample to solution ratio of 1:400 at room temperature. 7 mL of aliquots were pipetted out from the supernatant solution after 5, 24, 48, 72, 120, 144, and 168h. The extract was filtered and analysed for amorphous silicon using ICP-OES.

Fig.3.5: Flow chart of silicon fractionation from soil



$$\textbf{Residual Si} = \textbf{Total Si-} (\textbf{Si}_{m} + \textbf{Si}_{ad} + \textbf{Si}_{org} + \textbf{Si}_{occ} + \textbf{Si}_{amr})$$

Residual silicon (Si_{res})

The residual silicon was estimated by subtracting the sum of Si_m+ Si_{ad}+ Si_{org}+ Si_{occ}+ Si_{amr} from total silicon. Total silicon was estimated by the procedure outlined by Tan (2000). The soil samples were digested with 48 per cent HF and estimated using ICP-OES.

3.3.2.3. Enzyme activity

Dehydrogenase, urease, and acid phosphatase activity were determined at four stages *viz*., before planting, at tillering, panicle initiation, and at harvest.

3.3.2.3.1. Dehydrogenase activity

The dehydrogenase activity was determined as per the procedure explained by Casida *et al*. (1964) and explained in 3.2.4.

3.3.2.3.2. Urease activity

The urease activity of the field samples were estimated according to the method outlined by Tabatabai and Bremner, 1972.

To 5g soil in a 50 mL volumetric flask, 0.2 mL toluene, and 9 mL of THAM buffer (Tris (hydroxymethyl) amino methane) were added and shaken for few seconds to mix the contents properly. Then, 0.2M urea (1 mL) solution was added and again swirled for few seconds and kept for incubation at 37 °C for 2h. After that, 35 mL of KCl-Ag_2SO_4 solution was added. Then the contents were mixed properly and allowed to stand until the contents got cooled to room temperature. Final volume was made up to 50 mL by the addition of KCl-Ag_2SO_4 solution. 20 mL of aliquot of the suspension was pipetted into a 100 mL distillation flask and determined the ammoniacal nitrogen released by steam distillation of this aliquot with 0.2 g of MgO for four minutes.

Controls were performed as per the same procedure described for assay of urease activity. But 1 mL of 0.2M urea solution was added after the addition of 35 mL of KCl-Ag_2SO_4 solution.

3.3.2.3.3. Phosphatase activity

Phosphatase activity was estimated as per the procedure defined by Tabatabai and Bremner, 1969.

For each sample, two sets of 1 g soil were weighed in 50 mL volumetric flasks. Among the two, one was kept as control. Toluene (0.2 mL) and MUB buffer at pH 6.5 (4 mL) were added to samples. After that for one set of samples, 1 mL of p- nitro phenyl phosphate solution was added. Contents were mixed properly and kept for 1h incubation. After that, 1 mL of $CaCl_2$ and 4 mL of 0.5 M NaOH were added. The contents were swirled for few seconds for mixing. In control, para nitro phenyl phosphate solution was added after incubation.

All the suspensions were filtered quickly through Whatmann No. 2 filter paper. The yellow colour intensity of the filtrate was measured using spectrophotometer at a wavelength of 440 nm.

3.3.2.4. Plant analysis

Plant samples were collected from each plot at tillering, panicle initiation, and at harvest of rice. The collected samples were washed thoroughly with water, put in paper bag and dried in an oven at 70±5 °C. They were then powdered in stainless steel grinder and used for the analysis (Table 3.11).

Table 3.11: Methods of plant analysis

Sl. No.	Element	Method
1.	Nitrogen	Estimated by CHNS analyser (Model: Elementar’s vario EL cube)
2.	Phosphorus	Single acid digestion of leaf sample followed by filtration. Vanabdomolybdate phosphoric yellow colour in nitric acid system (Piper, 1966)
3.	Potassium	Single acid digestion of leaf sample followed by filtration. Flame photometry determination (Jackson, 1958)
4.	Calcium and magnesium	Single acid digestion of leaf sample followed by filtration. The filtrate was collected, analysed using ICP-OES (Piper, 1966)
5.	Iron, manganese, copper, zinc, and boron	Single acid digestion of leaf sample followed by filtration. The filtrate was collected and analyzed using ICP-OES (Piper, 1966)
6.	Silicon	Ma *et al*. (2002). Estimation by ICP-OES

3.3.2.5. Biometric observations

The observations on number of tillers per hill, plant height, and dry matter production were recorded at tillering, panicle initiation and harvest.

3.3.2.6. Yield attributes and yield

Yield attributes like number of panicles /m^2, number of spikelets per hill, number of filled grains per panicle, chaff (%), and thousand grain weight were recorded. Grain and straw yield were estimated after the completion of crop.

3.3.2.7. Nutrient uptake

From the nutrient content, uptake was worked out using the given formula.

$$\text{Nutrient uptake} = \frac{\text{Nutrient content (\%) x Dry matter (kg ha}^{-1}\text{)}}{100}$$

3.3.2.8. Incidence of pest and diseases, if any

Pests and diseases were noticed in the crop during the experimental period (Plate 3. 23-3.26) and were controlled by adopting timely measures.

Pest incidence

During the vegetative stage, incidence of leaf folder attack (leaves of plant are seen folded, rolled and often webbed together with white patches) was noticed. Rice bug attack was noticed during milky and grain filling stage of rice and grains showed brownish discoloured patches on the husk.

Disease incidence

Bacterial leaf blight and false smut were noticed during the vegetative and reproductive stage of rice, respectively.

3.4. STATISTICAL ANALYSIS

Analysis of variance in CRD and RBD was made in WASP package. Correlation analysis of data generated in various experiments was carried out based on the method suggested by Cox (1987) using SPSS package.

Plate 3. 23: Leaf folder infested rice plant

Plate 3. 24: Rice bug attack on grain

Plate 3.25: False smut infected panicle

Plate 3. 26: Bacterial leaf blight infected rice

RESULTS

4. RESULTS

The results pertaining to the study on "Nutrient dynamics and crop productivity in lowland lateritic soil (AEU 10) under rice residue management practices" are presented in this section. The study comprised of three experiments *viz.,* 1. characterization of rice residues and their products for physical and chemical properties, 2. an incubation experiment to study the kinetics of carbon mineralization 3. a field study to evaluate the efficacy of rice residues and their products in lowland rice.

4.1. CHARACTERIZATION

4.1.1. Characterization of rice residues

The major physical, electro-chemical, and chemical characteristics of rice residues (straw and husk) were characterized before the commencement of the experiment and the results are presented in Table 4.1.

The moisture content of straw and husk were 7.24 per cent and 6.03 per cent, respectively. Straw and husk were yellow coloured. Bulk density of straw was 0.80 Mg m^{-3} and that of husk was 0.89 Mg m^{-3}.

In case of electro-chemical properties, the pH of straw and husk was 7.81 and 7.24, revealing their alkaline nature, whereas the electrical conductivity was 0.50 dSm^{-1} and 0.36 dS m^{-1} for straw and husk, respectively.

Looking into the composition in terms of carbon, primary, secondary, micronutrients and silicon, it could be seen that the rice straw contained 36.45 per cent C, 0.52 per cent N, 0.20 per cent P, 1.29 per cent K, 548.32 mg kg^{-1} Ca, 269.20 mg kg^{-1} Mg, 530.08 mg kg^{-1} S, 432.01 mg kg^{-1} Fe, 80.24 mg kg^{-1} Mn, 2.23 mg kg^{-1} Cu, 23.26 mg kg^{-1} Zn, 3.86 mg kg^{-1} B, and 5.08 per cent silicon. Whereas, the rice husk contained 35.22 per cent C, 0.41 per cent N, 0.21 per cent P, 0.26 per cent K, 132.47 mg kg^{-1} Ca, 127.14 mg kg^{-1} Mg, 536.83 mg kg^{-1} S, 152.62 mg kg^{-1} Fe, 38.14 mg kg^{-1} Mn, 1.26 mg kg^{-1} Cu, 7.18 mg kg^{-1} Zn, 4.28 mg kg^{-1} B, and 8.23 per cent silicon. Cellulose and lignin content of straw was 38.10 per cent and 13.26 per cent, respectively. Whereas, 40.36 per cent cellulose and 27.82 per cent lignin was present in husk. The C: N ratio of straw was 71.20 and that of husk 86.01. Based on the weighted average of nutrient and structural composition scores, straw (140.73) was found to be superior to husk (82.38).

Table 4.1: Characteristics of rice residues

Parameters		Rice residues	
		Rice straw	Rice husk
1.Physical properties			
Moisture (%)		7.24	6.03
Colour		Yellow	Yellow
Odour		Absence of foul odour	Absence of foul odour
Bulk density (Mg m^{-3})		0.80	0.89
2. Electro-chemical properties			
pH		7.81	7.24
EC (dS m^{-1})		0.50	0.36
3. Chemical properties			
C	%	36.45	35.22
N		0.52	0.41
P		0.20	0.21
K		1.29	0.26
Ca	mg kg^{-1}	548.32	132.47
Mg		269.20	127.14
S		530.08	536.83
Fe		432.01	152.62
Mn		80.24	38.14
Cu		2.23	1.26
Zn		23.26	7.18
B		3.86	4.28
Silicon	%	5.08	8.23
Cellulose		38.10	40.36
Lignin		13.26	27.82
C/N ratio		71.20	86.01

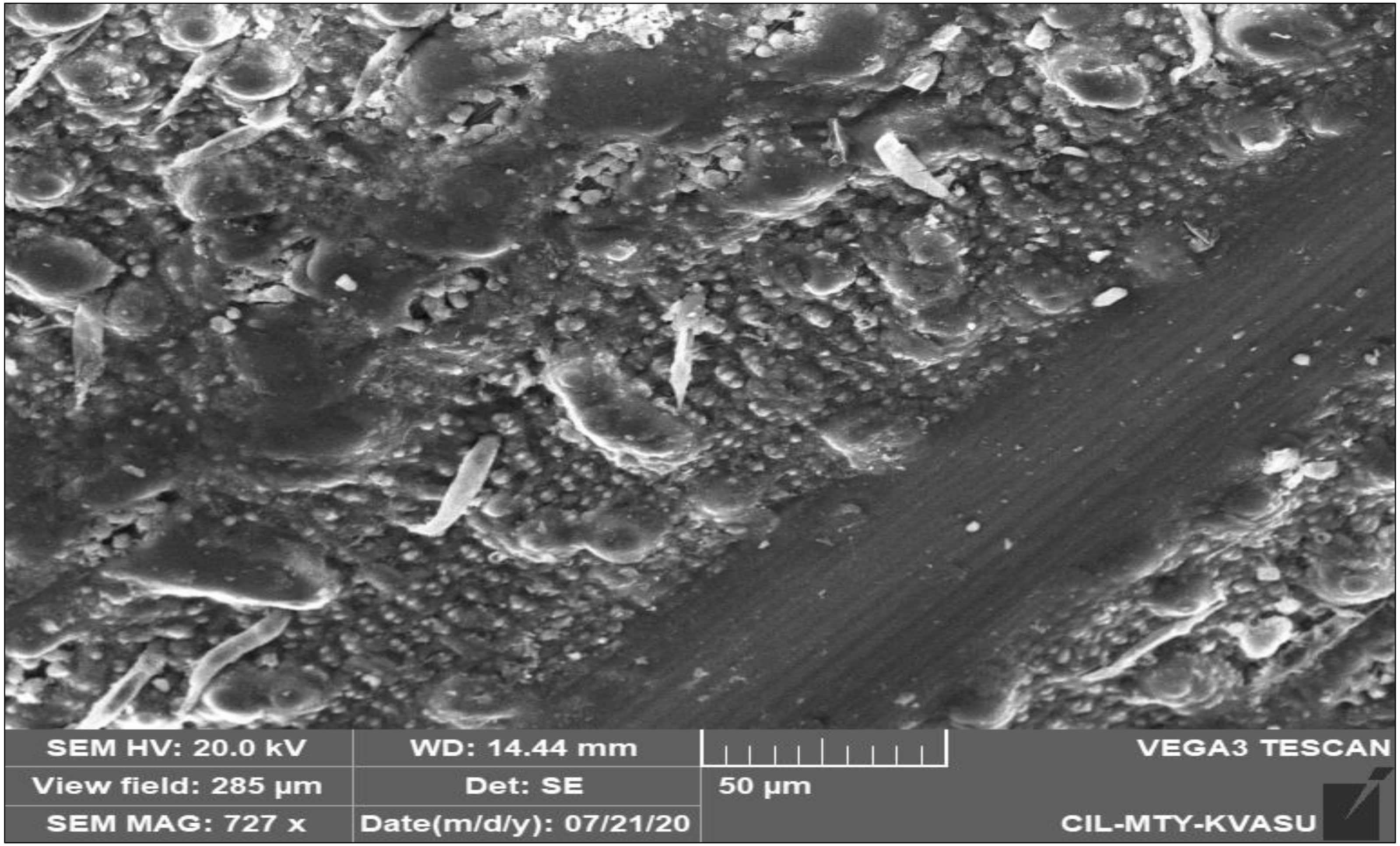


Plate 4.1: SEM micrograph of rice straw

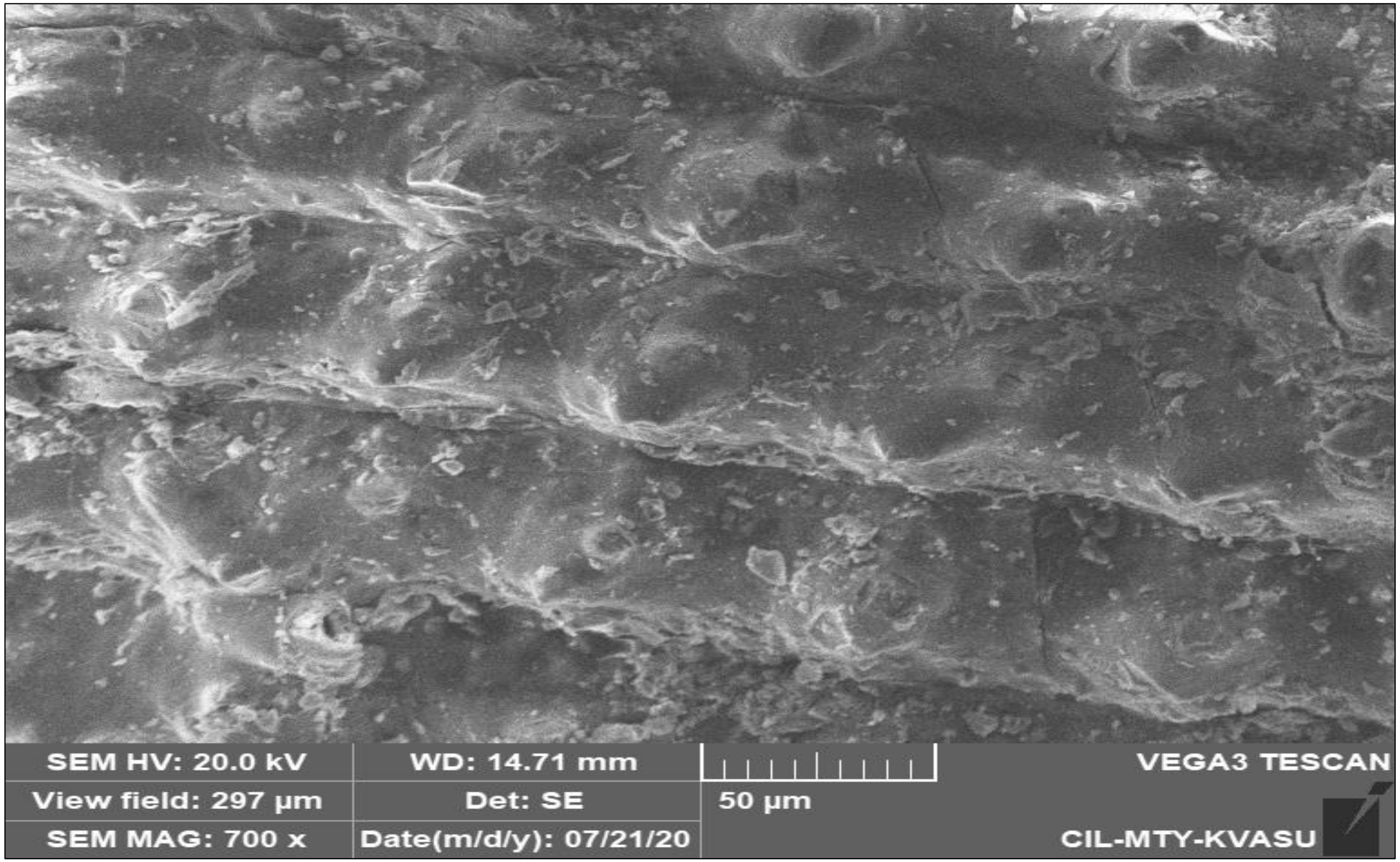


Plate 4.2: SEM micrograph of rice husk

Surface morphology or physical structure of rice residues were examined using scanning electron microscope (SEM) that scans a focussed beam of electrons over a surface for creating an image. The electrons interact with atoms in the sample, producing various signals that contain information about the surface topography and composition.

Plate 4.1 shows the micrograph of rice straw at 50 µm resolution wherein, the composition of plant cell wall can be clearly seen along with the epidermis, vascular bundles and parenchyma adhering to the bundle surface. The structure appeared rather rigid and compact with the surface possessing a coarse feel clearly revealing the long and thick fibres.

SEM image of rice husk exhibited well- arranged micro-bumps on the surface. The epidermis appeared as a rigid structure. The cellular arrangement pattern of the epidermis outer surface was also quite clear. In addition, the regular spherical pellets of almost equal size could be spotted in parallel rows (Plate 4.2).

In order to identify the functional groups present in rice straw and husk, FT-IR analysis was done. FT-IR is a form of vibrational spectrum that relies on the absorbance, transmittance and reflectance of infra-red light. It gives an idea on the structural chemistry of a substance. Fourier transform infra-red spectrum of straw for functional groups is presented in Fig. 4.1. The strong peak at 3338.45 cm^{-1} represented the O-H / N-H stretching vibrations. The peaks at 2956.23 cm^{-1} and 2850.98 cm^{-1} are assigned to aliphatic C-H stretching. The stretching of C=O bond and C=C alkene bond was observed at 1720.96 cm^{-1} and 1640.83cm^{-1} respectively. The peaks observed at 1528.96 cm^{-1}, 1448.56 cm^{-1}, and 1400.01 cm^{-1} reflected the C=C stretching of aromatic components. The peaks at 1356.48 cm^{-1} and 1322.21 cm^{-1} are assigned to C-H stretching out of plane vibration. The peak at 1208.56 cm^{-1} indicated C-O-C stretching. The strong peak at 1037.22 cm^{-1} designated to Si-O-Si stretching, a characteristic feature of rice residues. The peak at 780.88 cm^{-1} represented the Si-H stretching. The peaks at 949.18 cm^{-1}, 648.87 cm^{-1}, 553.24 cm^{-1}, and 470.84 cm^{-1} are assigned to C-H stretching out of plane vibration.

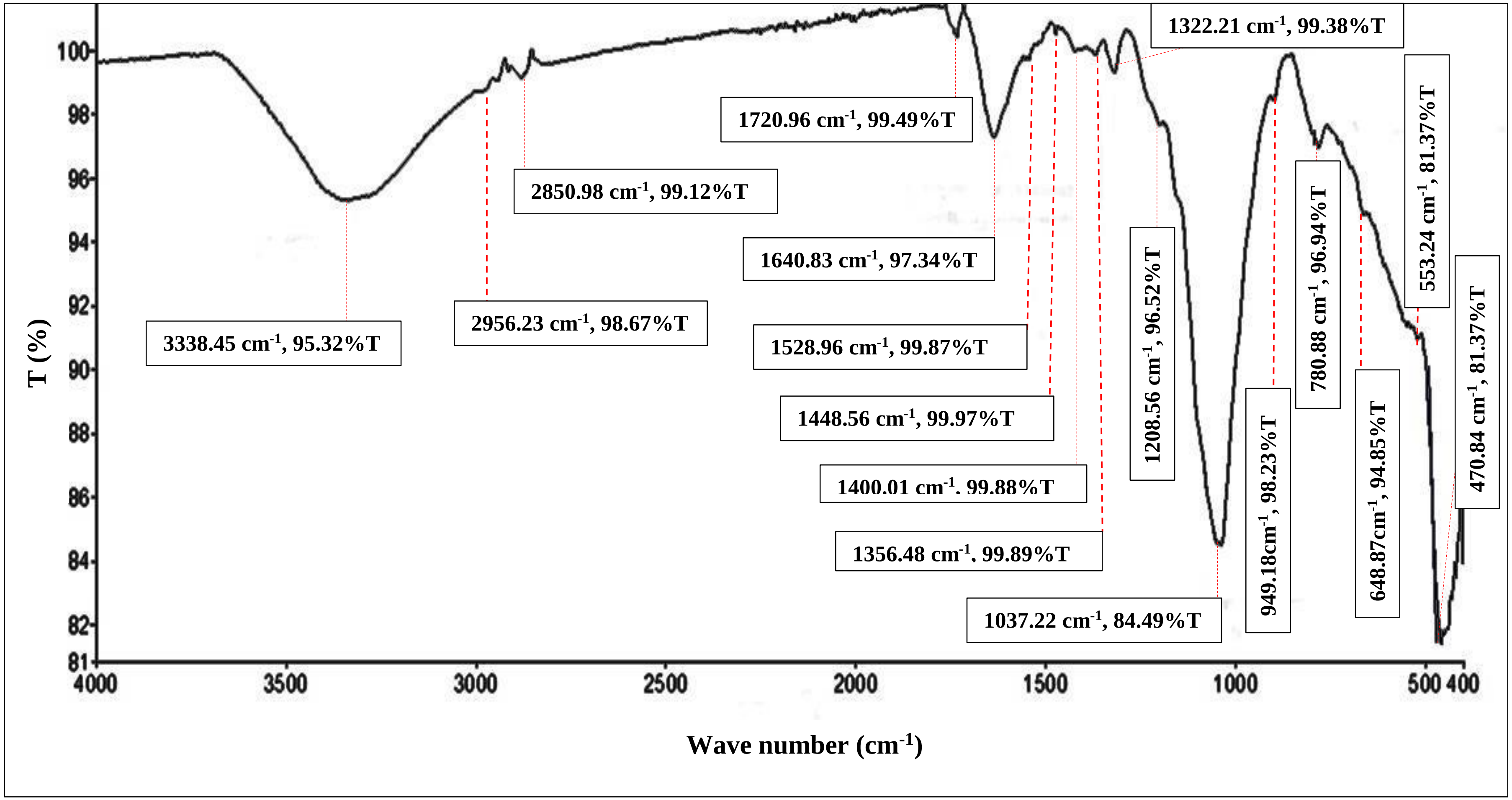


Fig.4.1: Fourier-transform infrared (FT-IR) spectrum of rice straw

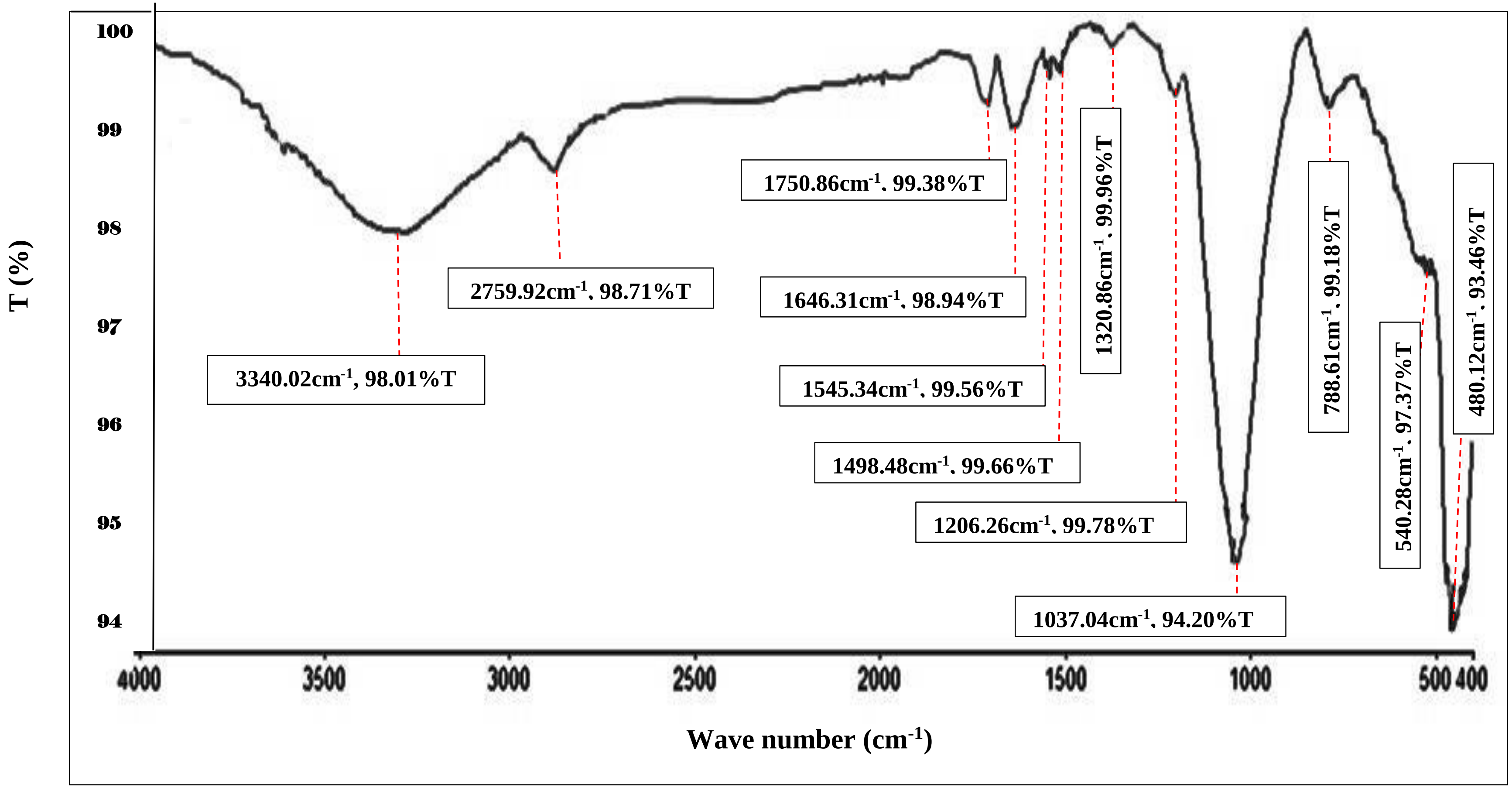


Fig.4.2: Fourier-transform infrared (FT-IR) spectrum of rice husk

Fig. 4.2 shows the FT-IR spectrum of rice husk, in which the peak at 3340.02 cm^{-1} indicated the presence of O-H/N-H stretching. And the one at peak at 2759.92 cm^{-1} represented aliphatic C-H stretching. The peak at 1750.86 cm^{-1} could be C=O stretching. The C=C alkene stretching was observed at 1646.31 cm^{-1} of FT-IR spectrum. The peaks at 1545.34 cm^{-1} and 1498.48 cm^{-1} are assigned to C=C aromatic stretching. The peak at 1206.26 cm^{-1} indicated the presence of C-O-C stretching. The characteristic Si-O-Si and Si-H stretching was observed at 1037.04 cm^{-1} and 788.61 cm^{-1} respectively. The peaks at 540.28 cm^{-1} and 480.12 cm^{-1} are assigned to C-H stretching out of plane vibration.

4.1.2. Production and characterization of straw and husk vermicompost

Vermicomposted straw (VRS) and vermicomposted husk (VRH) used in the present study was prepared from rice straw and husk, respectively, in the vermicomposting unit of College of Agriculture, Vellanikkara, Kerala Agricultural University. Recovery of VRS and VRH were, on an average, 74.38 per cent and 70.03 per cent, respectively. The vermicompost produced from both the residues were sieved through a 2 mm sieve, after an initial sieving in the unit, and stored for further studies in the laboratory.

Various parameters like moisture content, colour, odour, particle size, bulk density, pH, EC, total C, N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, B, C:N ratio, silicon, cellulose and lignin were analysed in order to evaluate the physical, electro-chemical and chemical characteristics of vermicompost produced from rice straw and rice husk. The results obtained are presented in Table 4.2.

The moisture content of vermicomposted rice straw (VRS) and vermicomposted rice husk (VRH) was 23.68 per cent and 18.94 per cent, respectively. The colour of VRS and VRH was brown. No foul odour was noticed in both type of composts. Particle size determination following FCO specification revealed 100 per cent of the composted material passing through 4.0 mm IS sieve. The bulk density of VRS and VRH were 0.78 Mg m^{-3} and 0.72 Mg m^{-3}, respectively.

The produced vermicomposts (VRS and VRH) were alkaline in nature with VRS registering a pH of 8.71 and VRH 7.97, respectively. The highest electrical conductivity was associated with VRS (1.15 dSm^{-1}) as against VRH (1.03 dSm^{-1}).

Table 4.2: Characteristics of vermicompost

Parameters		Vermicomposted rice straw (VRS)	Vermicomposted rice husk (VRH)
1.Physical properties			
Moisture (%)		23.68	18.94
Colour		Brown	Brown
Odour		Absence of foul odour	Absence of foul odour
Particle size		100 % of materials passed through 4.0mm IS sieve	
Bulk density (Mg m^{-3})		0.78	0.72
2. Electro-chemical properties			
pH		8.71	7.97
EC (dS m^{-1})		1.15	1.03
3. Chemical properties			
C	%	18.25	31.75
N		1.23	0.72
P		0.34	0.26
K		1.31	0.27
Ca	mg kg^{-1}	582.45	132.68
Mg		370.17	130.01
S		540.00	542.76
Fe		441.26	159.34
Mn		83.92	42.17
Cu		2.46	1.48
Zn		24.01	7.24
B		3.89	4.31
Silicon	%	8.37	8.26
Cellulose		12.26	20.84
Lignin		6.84	21.75
C/N ratio		14.83	44.09

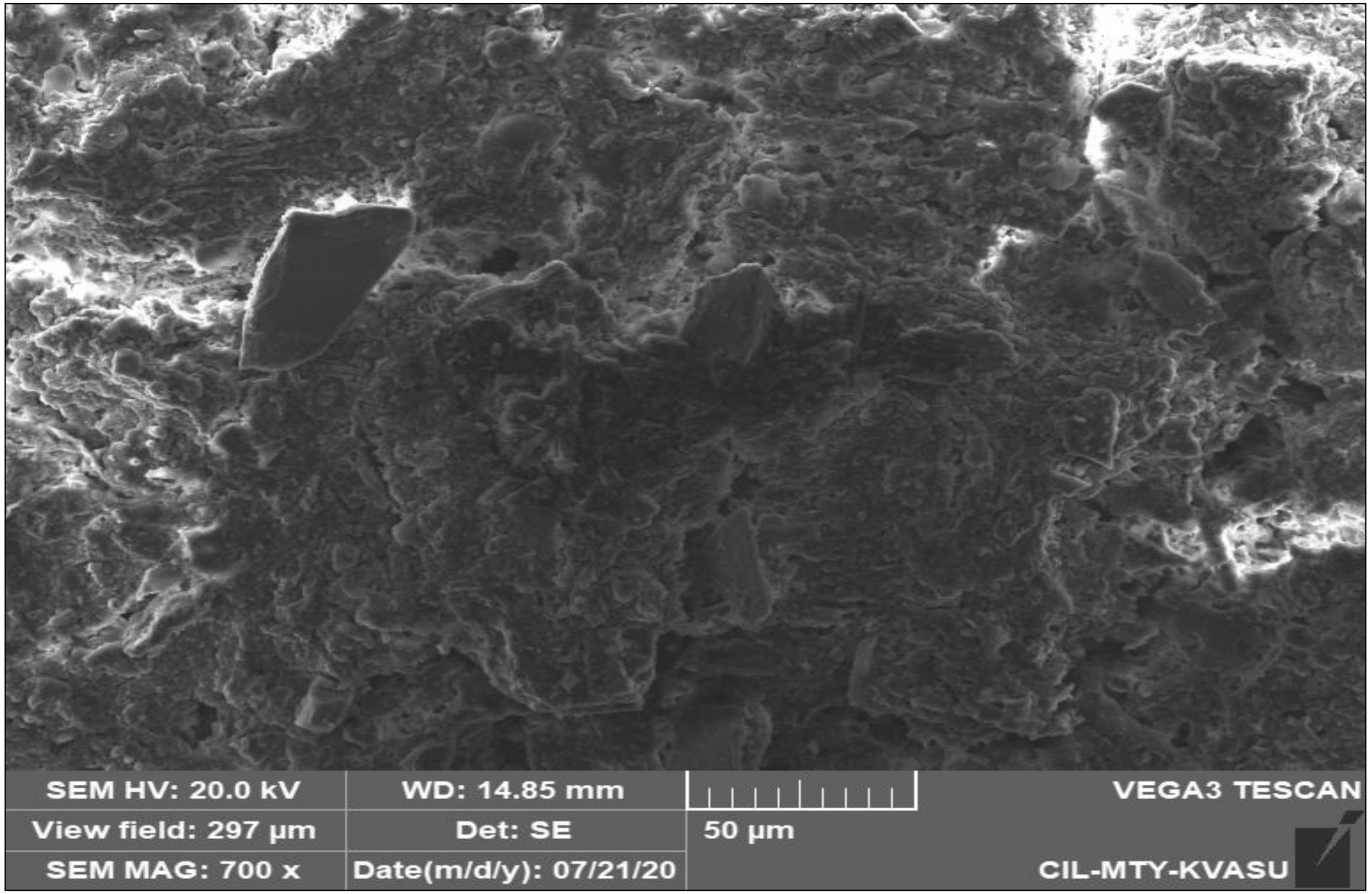


Plate 4.3: SEM micrograph of rice straw vermicompost

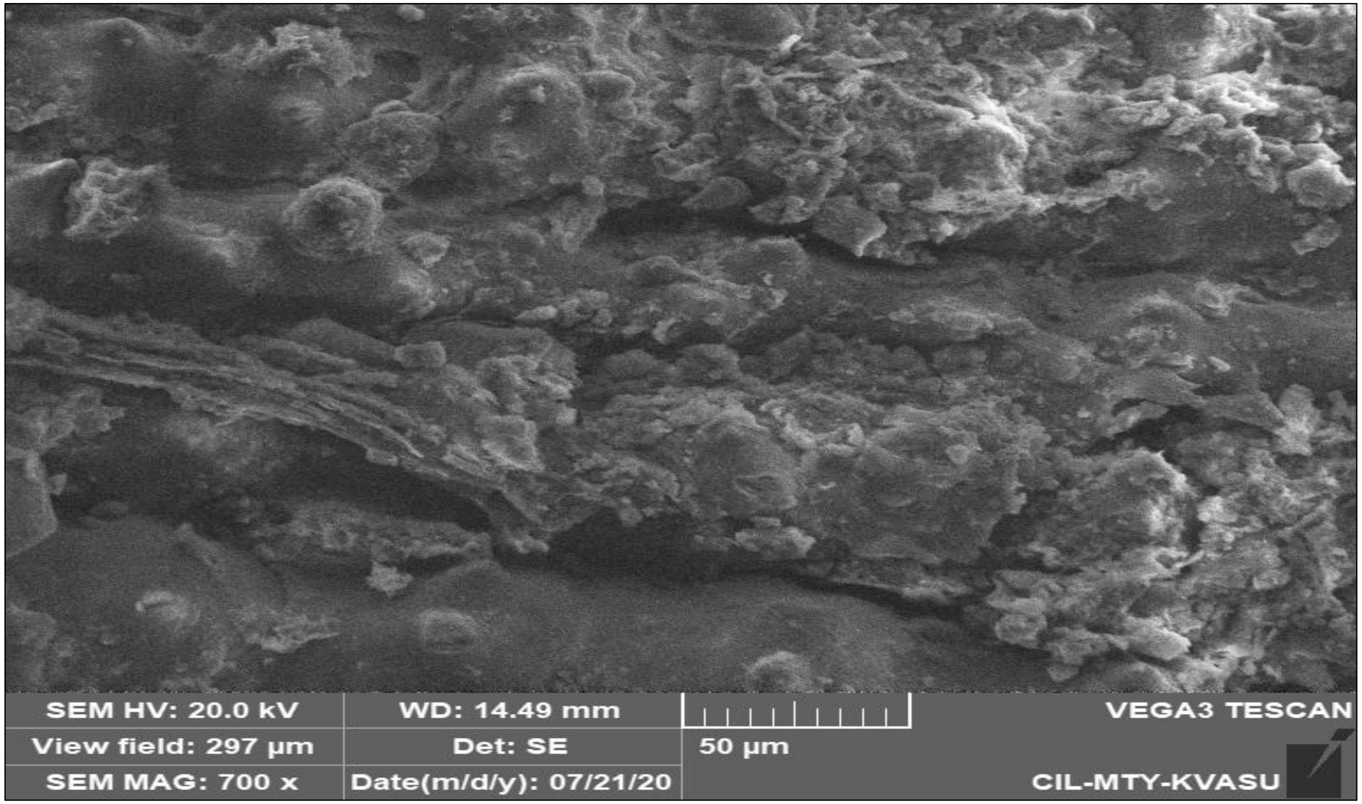


Plate 4.4: SEM micrograph of rice husk vermicompost

The process of vermicomposting helped to bring down the C: N ratio of the raw materials from an initial value of 71.20 and 86.01 in rice straw and rice husk to 14.83 and 44.09, respectively, with the effect being more pronounced in vermicomposted rice straw as against vermicomposted rice husk. The content of carbon was 18.25 and 31.75 per cent, respectively in VRS and VRH.

Vermicomposted rice straw contained significant amounts of macro nutrients *viz*., 1.23 per cent N, 0.34 per cent P, 1.31 per cent K, 582.45 mg kg^{-1} Ca, 370.17 mg kg^{-1} Mg, and 540.00 mg kg^{-1} S. The content of micronutrients in VRS were 441.26 mg kg^{-1} Fe, 83.92 mg kg^{-1} Mn, 2.46 mg kg^{-1} Cu, 24.01 mg kg^{-1} Zn, and 3.89 mg kg^{-1} B.

The macronutrient content of VRH was 0.72 per cent N, 0.26 per cent P, 0.27 per cent K, 132.68 mg kg^{-1} Ca, 130.01 mg kg^{-1} Mg, and 542.76 mg kg^{-1} S. Whereas, the micronutrient concentration was 159.34 mg kg^{-1}Fe, 42.17 mg kg^{-1}Mn, 1.48 mg kg^{-1}Cu, 7.24 mg kg^{-1}Zn, and 4.31 mg kg^{-1}B.

The silicon content in VRS was 8.37 per cent and that in VRH was 8.26 per cent. The content of cellulose and lignin was highest in VRH (20.84 % cellulose and 21.75 % lignin) compared to VRS (12.26 % cellulose and 6.84 % lignin).

SEM micrograph of vermicomposted rice straw (Plate 4.3) showed highly fragmented, disaggregated and porous structure. This was not much visible in the micrograph of vermicomposted rice husk and the undecomposed husk was clearly noted in the image (Plate 4.4).

The FT-IR technique is an important tool to identify the characteristic functional groups. The FT-IR spectrum of vermicomposted rice straw (VRS) was shown in Fig. 4.3. The spectrum resembles that of rice straw but some differences like disappearance of bands and shifting were detected in the spectrum of VRS. The strong peak at 3347.66 cm^{-1} represented O-H/N-H stretching. The peaks at 2943.75 cm^{-1} and 2896.31 cm^{-1} are assigned to aliphatic C-H stretching. A strong peak of C=C alkene stretching was found at 1632.63 cm^{-1}. The moderate peak at 1380.16 cm^{-1} represented C-H stretching out of plane vibration.

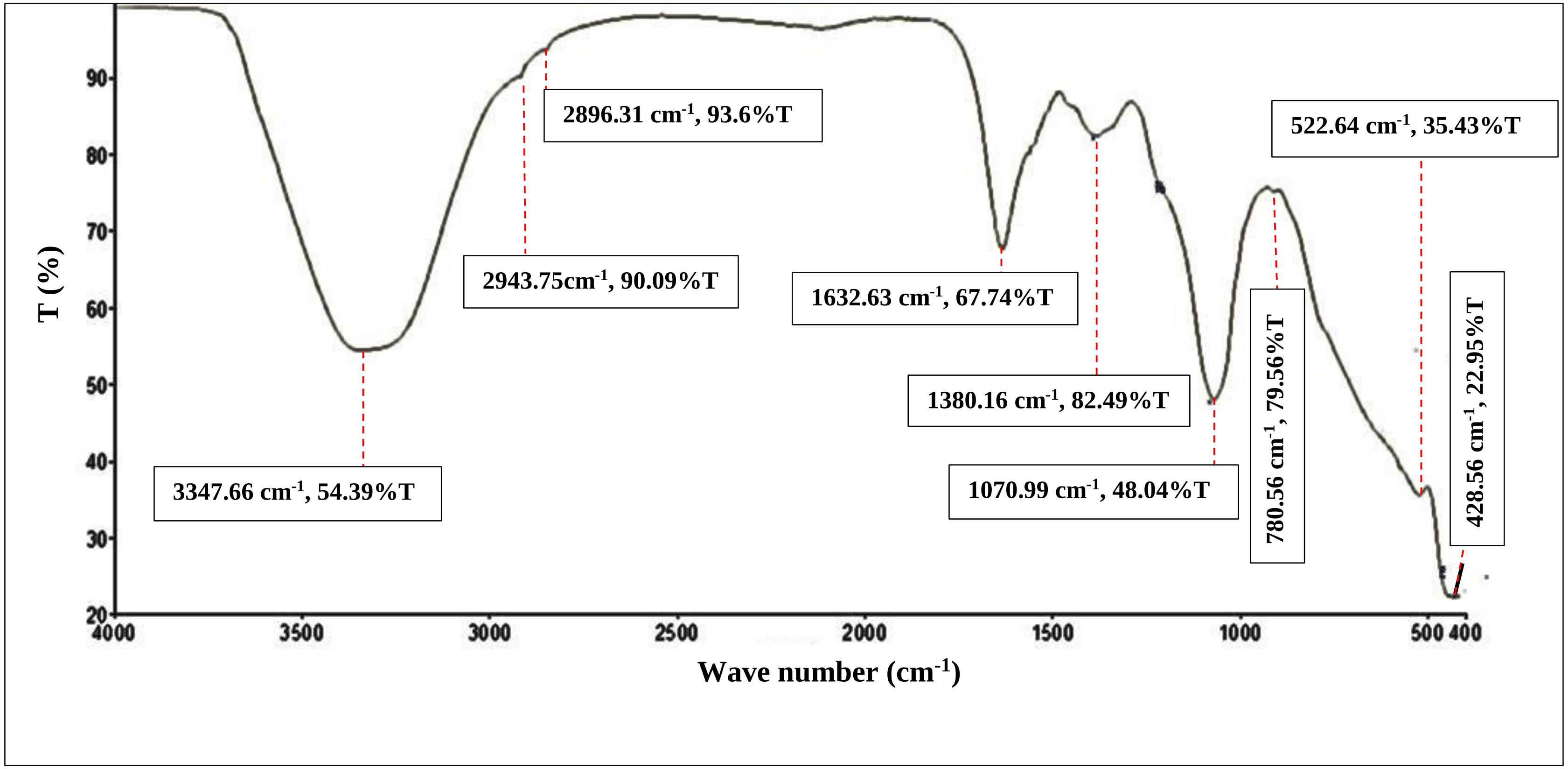


Fig. 4.3: Fourier-transform infrared (FT-IR) spectrum of vermicomposted rice straw

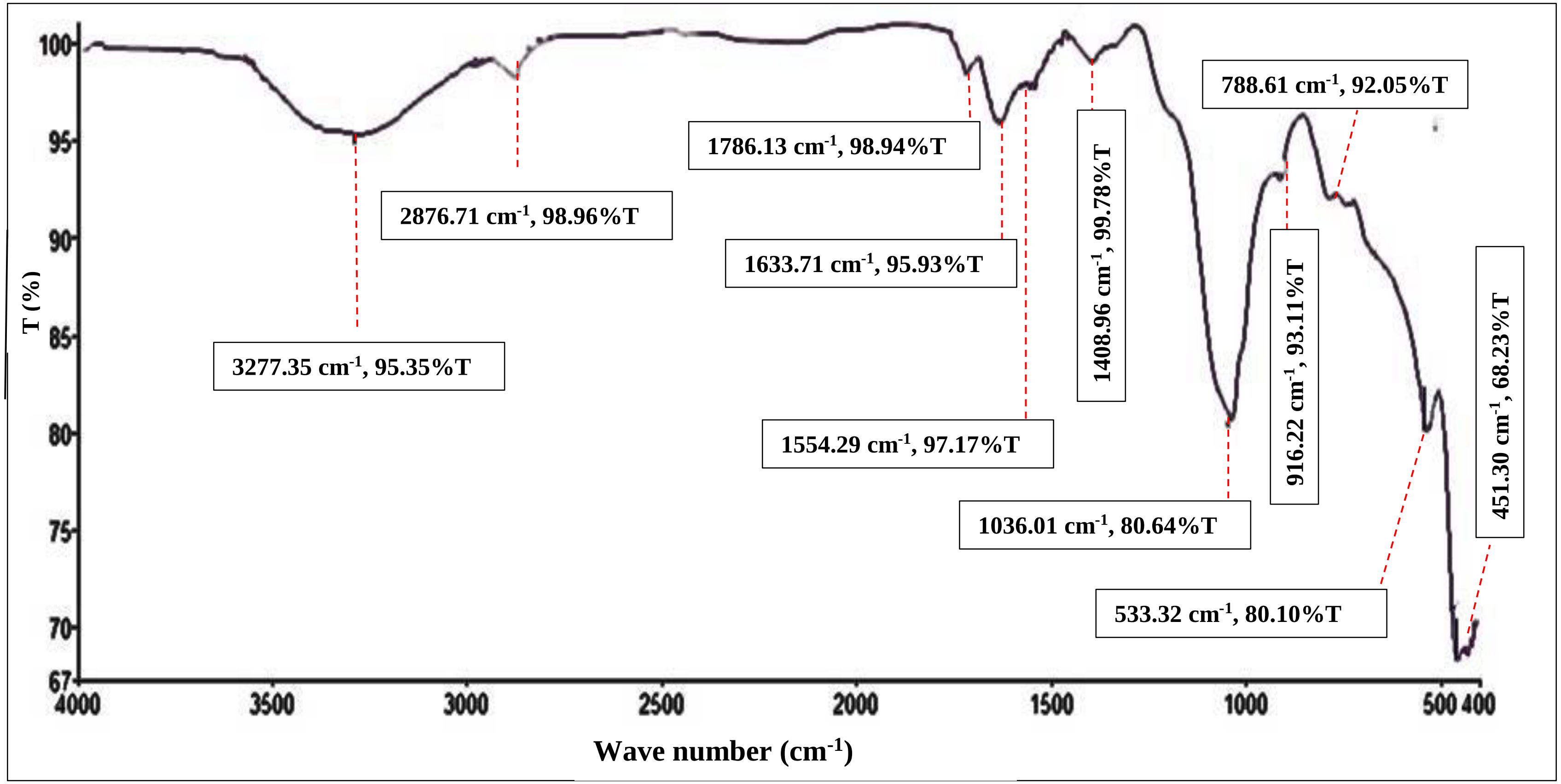


Fig.4.4: Fourier-transform infrared (FT-IR) spectrum of vermicomposted rice husk

The strong peak at 1070.99 cm^{-1} represented Si-O-Si stretching and weak peak at 780.56 cm^{-1} represents Si-H stretching. The peaks at 522.64 cm^{-1} and 428.56 cm^{-1} are assigned to C-H stretching out of plane vibration.

The FT-IR spectrum of vermicomposted rice husk (VRH) was shown in Fig.4.4. Compared to husk, vermicomposting resulted in the disappearance and shifting of some peaks. The peak at 3277.35 cm^{-1} indicated O-H/N-H stretching vibration. The peak at 2876.71 cm^{-1} was attributed to aliphatic C-H stretching. The peak at 1786.13 cm^{-1} represented C=O stretching. The peak at 1633.71 cm^{-1} corresponded to C=C alkene stretching. The peaks at 1554.29 cm^{-1} and 1408.96 cm^{-1} are assigned to C=C aromatic stretching. The peaks at 1036.01 cm^{-1} and 788.61 cm^{-1} are stretching of Si-O-Si and Si-H respectively. The peaks at 916.22 cm^{-1}, 533.32 cm^{-1}, and 451.30 cm^{-1} were attributed to C-H stretching out of plane vibration.

4.1.3. Production and characterization of straw and husk biochar

Straw and husk biochar used in the present study was prepared by the process of pyrolysis in a kiln exclusively designed for the production purpose. Biochar thus obtained was cooled, powdered, sieved through 2mm sieve and characterized for physical, electrochemical, and chemical properties in the laboratory. The analytical data are presented in Table 4.3.

On an average, 38 per cent rice husk biochar (RHB) and 19.86 per cent rice straw biochar (RSB) could be recovered from the husk and straw, respectively.

The moisture content in the RSB was 3.62 per cent and it was 4.68 per cent in RHB. The biochar produced from both rice straw and husk was black in colour and free from any foul odour. Hundred per cent of the material passed through 4mm IS sieve. As regards to bulk density, it could be seen that it was more in RSB (0.64 Mg m^{-3}) as against RHB (0.59Mgm^{-3}).

In respect of electro-chemical properties, the pH of RSB and RHB was 9.24 and 9.20, respectively and electrical conductivity was 0.51 dS m^{-1} and 0.86 dS m^{-1} in the RHB and RSB, respectively.

Table 4.3: Characteristics of biochar

Parameters		Rice straw biochar (RSB)	Rice husk biochar (RHB)
1.Physical properties			
Moisture (%)		3.62	4.68
Colour		Black	Black
Odour		Absence of foul odour	Absence of foul odour
Particle size		100 % of materials passed through 4.0mm IS sieve	
Bulk density (Mg m^{-3})		0.64	0.59
2. Electro-chemical properties			
pH		9.24	9.20
EC (dS m^{-1})		0.86	0.51
3. Chemical properties			
C	%	35.15	34.86
N		0.40	0.32
P		0.22	0.24
K		1.34	0.30
Ca	mg kg^{-1}	548.26	131.06
Mg		260.02	126.28
S		528.98	536.12
Fe		429.75	149.57
Mn		78.53	36.01
Cu		2.01	1.10
Zn		23.15	7.15
B		3.84	4.25
Silicon	%	10.21	13.87
Cellulose		2.81	4.06
Lignin		4.74	13.06
C/N ratio		87.88	108.94

The nutrients contained in RSB were: 35.15 per cent C, 0.40 per cent N, 0.22 per cent P, 1.34 per cent K, 548.26 mg kg^{-1} Ca, 260.02 mg kg^{-1} Mg, 528.98 mg kg^{-1} S, 429.75 mg kg^{-1} Fe, 78.53 mg kg^{-1} Mn, 2.01 mg kg^{-1} Cu, 23.15 mg kg^{-1} Zn, 3.84 mg kg^{-1} B, and 10.21 per cent Si. Much alike RSB, the RHB contained nutrients to the extent of 34.86 per cent C, 0.32 per cent N, 0.24 per cent P, 0.30 per cent K, 131.06 mg kg^{-1} Ca, 126.28 mg kg^{-1} Mg, 536.12 mg kg^{-1} S, 149.57 mg kg^{-1} Fe, 36.01 mg kg^{-1} Mn, 1.10 mg kg^{-1} Cu, 7.15 mg kg^{-1} Zn, 4.25 mg kg^{-1} B, and 13.87 per cent Si.

Cellulose and lignin content of RHB was 4.06 per cent and 13.06 per cent, respectively. While it was only 2.81and 4.74 per cent each in case of RSB because of which the C: N ratio registered a higher value of 108.94 in RHB in contrast to 87.88 in RSB.

External morphology of biochar was studied in depth using scanning electron microscope. The SEM image of RSB exhibited a highly disordered and complex morphology with longitudinal channels and pores under 50 µm resolution (Plate 4.5). The particles gave a broken or distorted appearance thus resembling the plant structure with remains of vessels, the larger diameter tubes used for the transport of fluids and nutrients. The SEM image of RHB (Plate 4.6) exhibited a highly porous and fragmented structure.

Fig. 4.5 displayed the FT-IR spectrum of rice straw biochar (RSB). Charring of straw caused characteristic changes the spectrum of RSB. No peak was observed in the region of 3000 cm^{-1} - 4000 cm^{-1}. The peak at 2840.98 cm^{-1} represented aliphatic C-H stretching. The peak at 1780.01 cm^{-1} indicated C=O stretching. The peak at 1623.79 cm^{-1} assigned to C=C stretching and peaks at 1586.23 cm^{-1} and 1396.21 cm^{-1} are attributed to C=C aromatic stretching. A weak peak at 1201.13 cm^{-1} indicated C-O-C stretching. The peaks at 1047.15 cm^{-1} and 784.75 cm^{-1} are assigned to Si-O-Si and Si-H stretching respectively. The C-H stretching out of plane vibration was noticed in the spectrum and it was evidenced from the peak at 477.80 cm^{-1}.

Changes in FT-IR spectral properties of RHB after pyrolysis of husk are presented in Fig.4.6. The disappearance as well as appearance of peaks and peak shifting was observed after charring. The peak assigned to O-H/N-H stretching (3000 cm^{-1} - 4000 cm^{-1}) was not observed in the spectrum. The weak peak at 2810.91 cm^{-1} represented aliphatic C-H stretching.

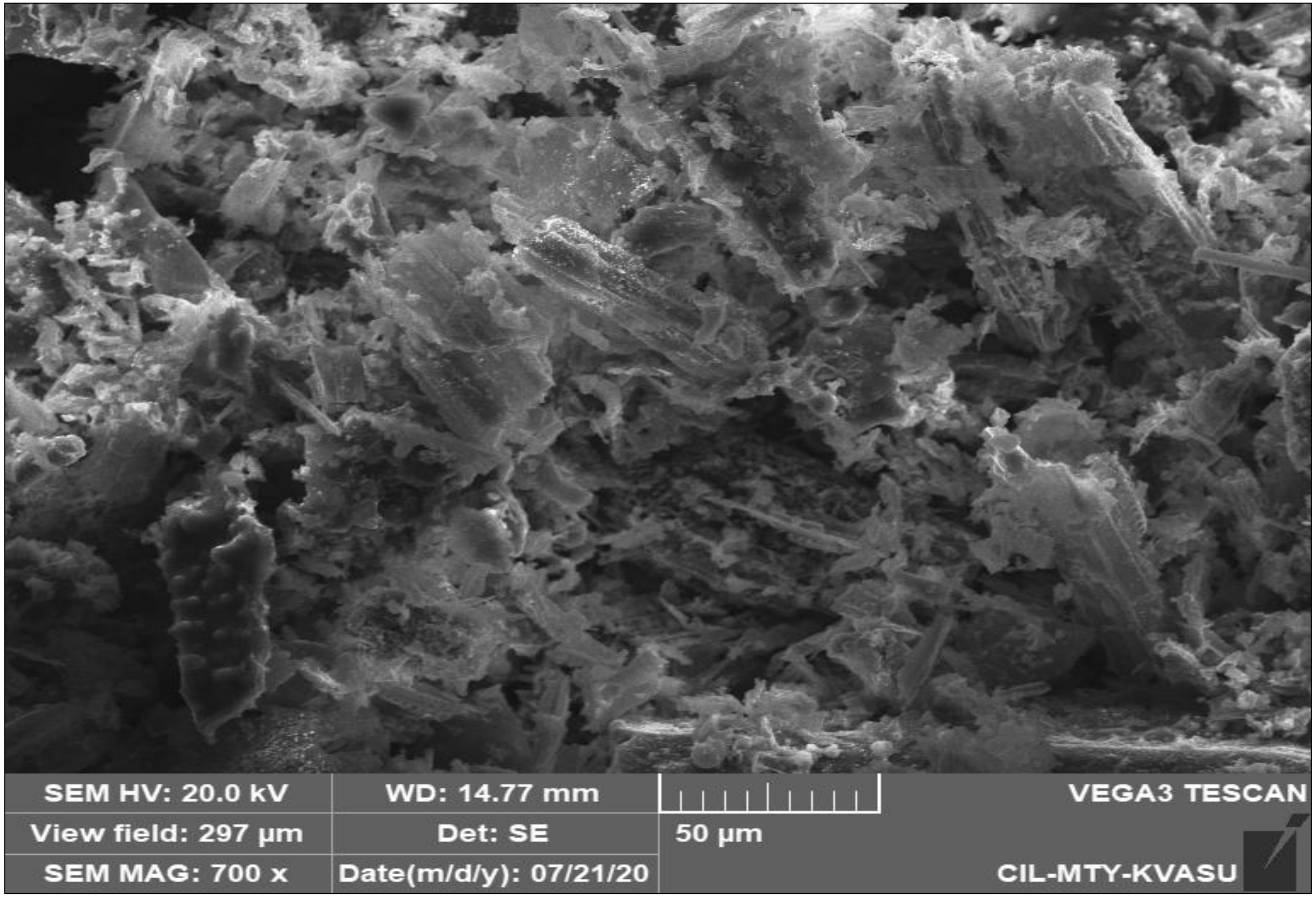


Plate 4.5: SEM micrograph of rice straw biochar

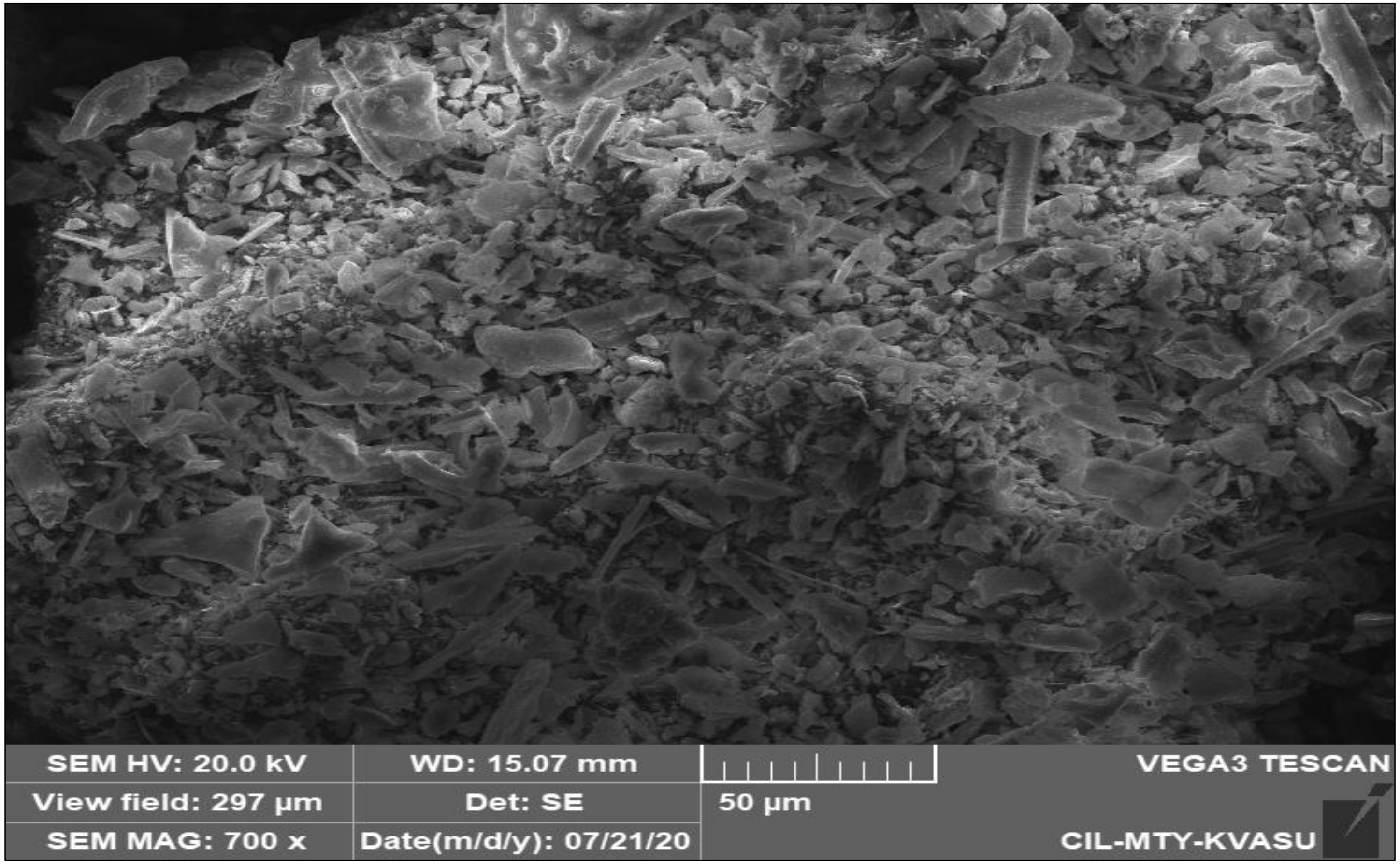


Plate 4.6: SEM micrograph of rice husk biochar

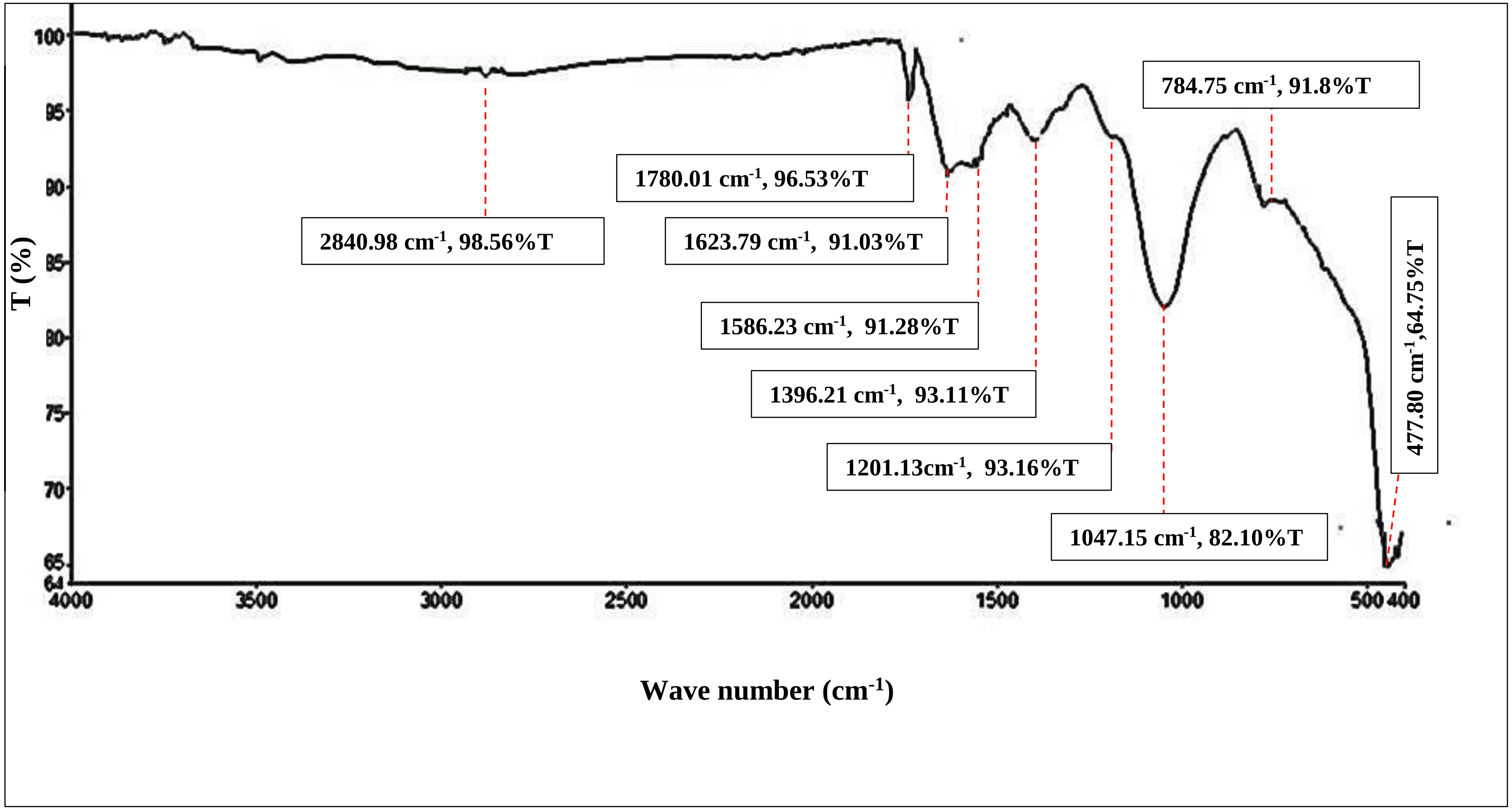


Fig. 4.5: Fourier-transform infrared (FT-IR) spectrum of rice straw biochar

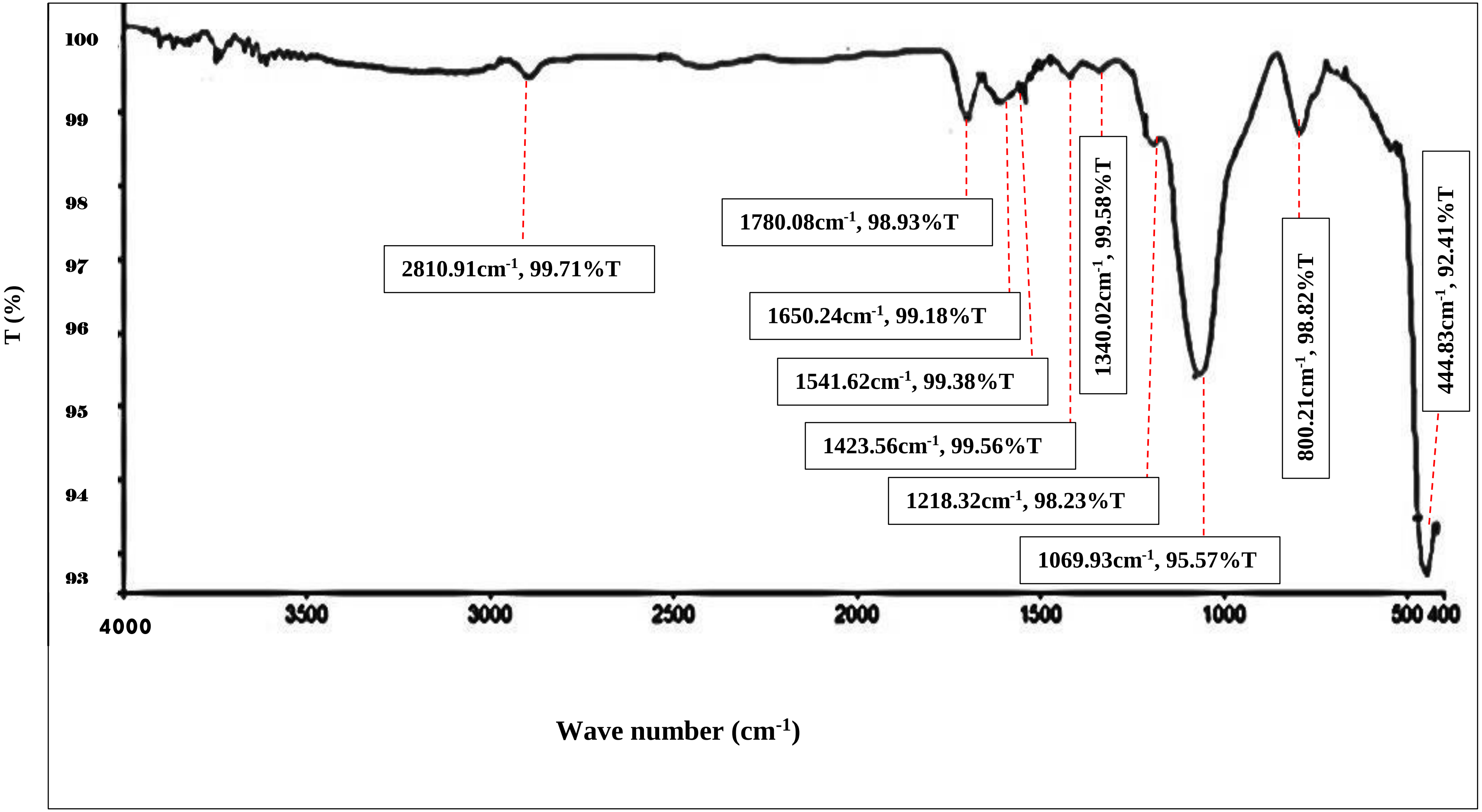


Fig.4.6: Fourier-transform infrared (FT-IR) spectrum of rice husk biochar

The peak at 1780.08 cm^{-1} indicated C=O stretching. The peak at 1650.24 cm^{-1} assigned to C=C alkene stretching. The peaks at 1541.62 cm^{-1} and 1423.56 cm^{-1} are attributed to C=C aromatic stretching. The C-H stretching out of plane vibration was evidenced from the peaks at 1340.02 cm^{-1} and 444.83 cm^{-1}. The peak at 1218.32 cm^{-1} indicated C-O-C stretching. The peaks at 1069.93 cm^{-1} and 800.21 cm^{-1} were indicated the presence of Si-O-Si and Si-H stretching.

4.2. INCUBATION EXPERIMENT

4.2.1. Carbon mineralization

The efflux of CO_2-C was estimated at frequent intervals for a period of 110 days. Carbon mineralization was determined using the first order kinetic equations at 15, 25, 35 and 45 ºC. Thermal sensitivity parameters Q_{10} and activation energy were also determined and the data are given in Tables 4.4-4.7.

The amount of CO_2-C mineralized during incubation increased with increasing temperature (Table 4.4). Vermicomposted rice straw treated soils registered higher mineralizable carbon at 15, 25, 35 and 45 ºC and the value varied as 40.61, 53.20, 79.79, and 104.61 mg CO_2-C per 100g soil, respectively. The potentially mineralizable carbon was lowest in absolute control at all the temperatures studied and were 29.83, 33.77, 35.16, and 40.25 mg CO_2-C per 100g soil each at 15, 25, 35 and 45 ºC, respectively.

Decomposition rate (Table 4.5) decreased in all treatments at 45 °C which might be due to the exhaustion of substrates or conversion of substrates to non-available forms for microbial decomposition. At 15 °C, the rate of decomposition was highest in vermicomposted rice treated soils and lowest in control. At 25 °C and 35 °C, vermicomposted rice straw and FYM treated soils had a higher decomposition rate than the other treatments. At higher temperature (45 °C), decomposition rate was highest in FYM treated soil and vermicomposted rice straw added soil and lowest in absolute control.

The activation energy in the different treatments (Table 4.6) varied from 7.21 kJ mol^{-1} to 12.79 kJ mol^{-1}. The more the activation energy, more is the thermal stability and vice versa. The highest activation energy was found in rice husk biochar amended soil (12.79 kJ mol^{-1}) followed by rice straw biochar amended soil (12.71 kJ mol^{-1}). The lowest activation energy was found in absolute control (7.21 kJ mol^{-1}).

Q_{10} values represent the temperature dependency of the reaction over a 10 °C rise in temperature. The results showed that all treatments had Q_{10} values <1 (Table 4.7) which confirms a decrease in relative reaction rate at higher temperatures.

Table 4.4: Potentially mineralizable carbon at different temperatures

Treatments	**Potentially mineralizable carbon (mg CO_2-C/100g soil)**			
	T_1(15 ºC)	T_2 (25 ºC)	T_3 (35 ºC)	T_4 (45 ºC)
S_1 (Absolute control)	29.83	33.77	35.16	40.25
S_2 (Soil+ RH)	33.10	34.49	36.79	44.89
S_3 (Soil+ RS)	33.13	34.51	37.00	45.10
S_4 (Soil+ VRH)	34.39	39.65	48.37	57.48
S_5 (Soil+ VRS)	40.61	53.20	79.79	104.61
S_6 (Soil+ RHB)	29.07	34.53	41.65	43.92
S_7 (Soil+ RSB)	29.95	35.20	41.79	43.96
S_8 (Soil+ FYM)	40.13	49.84	75.10	90.37
S_9 (Soil+ Nutrients)	30.52	33.99	36.60	40.27

Table 4.5. First order rate constants (k) of carbon mineralization at different temperatures

Treatments	**Rate constant (k) in mg g^{-1} C day^{-1}**			
	T_1(15 ºC)	T_2 (25 ºC)	T_3 (35 ºC)	T_4 (45 ºC)
S_1 (Absolute control)	0.0100	0.0089	0.0085	0.0074
S_2 (Soil+ RH)	0.0107	0.0104	0.0097	0.0074
S_3 (Soil+ RS)	0.0110	0.0105	0.0097	0.0077
S_4 (Soil+ VRH)	0.0160	0.0150	0.0120	0.0106
S_5 (Soil+ VRS)	0.0260	0.0230	0.0190	0.0170
S_6 (Soil+ RHB)	0.0150	0.0120	0.0104	0.0090
S_7 (Soil+ RSB)	0.0150	0.0120	0.0105	0.0090
S_8 (Soil+ FYM)	0.0250	0.0230	0.0190	0.0170
S_9 (Soil+ Nutrients)	0.0102	0.0091	0.0085	0.0076

Table 4.6. Activation energy (kJ mol^{-1}) of carbon mineralization in soil

Treatments	**Activation energy (kJmol^{-1})**
S_1 (Absolute control)	7.21
S_2 (Soil+ RH)	8.83
S_3 (Soil+ RS)	8.65
S_4 (Soil+ VRH)	11.06
S_5 (Soil+ VRS)	11.15
S_6 (Soil+ RHB)	12.79
S_7 (Soil+ RSB)	12.71
S_8 (Soil+ FYM)	10.24
S_9 (Soil+ Nutrients)	7.23

Table 4.7. Q_{10} values

Treatments	**Q_{10} values**		
	k_{25}/k_{15}	**k_{35}/k_{25}**	**k_{45}/k_{35}**
S_1 (Absolute control)	0.89	0.96	0.87
S_2 (Soil+ RH)	0.97	0.93	0.76
S_3 (Soil+ RS)	0.95	0.92	0.79
S_4 (Soil+ VRH)	0.94	0.80	0.88
S_5 (Soil+ VRS)	0.88	0.83	0.89
S_6 (Soil+ RHB)	0.80	0.87	0.87
S_7 (Soil+ RSB)	0.80	0.88	0.86
S_8 (Soil+ FYM)	0.92	0.83	0.89
S_9 (Soil+ Nutrients)	0.89	0.93	0.89

4.2.2. Dehydrogenase activity

The dehydrogenase activity was determined before and after the incubation experiment.

4.2.2.1. Dehydrogenase activity before incubation experiment

The enzyme activity recorded before incubation experiment are given in Table 4.8. The dehydrogenase activity varied from 36.43 to 37.83 µg TPF $g^{-1}day^{-1}$. Statistically no significant difference existed between the treatments before the start of incubation experiment.

Table 4.8: Dehydrogenase activity before incubation experiment

Treatments	**Dehydrogenase activity (µg TPF $g^{-1}day^{-1}$)**
Absolute control	36.43
Soil+ RH	36.43
Soil+ RS	36.43
Soil+ VRH	37.00
Soil+ VRS	37.83
Soil+ RHB	36.43
Soil+ RSB	36.43
Soil+ FYM	37.63
Soil+ Nutrients	36.43
CD (0.05)	NS

4.2.2.2. Dehydrogenase activity after incubation experiment

The data on dehydrogenase activity after 110 days of incubation period under different temperatures and treatments are shown in Table 4.9.

Dehydrogenase activity was found to be lowest at T_4 (45 ºC) with a mean value of 21.47 µg TPF $g^{-1}day^{-1}$ and the highest activity was observed at T_4 (15 ºC) with a mean value of 24.28 µg TPF $g^{-1}day^{-1}$ which was found to be statistically on par with dehydrogenase activity at T_3 (25 ºC) registering a mean value of 24.02 µg TPF $g^{-1}day^{-1}$.

Among the nine different treatment sources after incubation period, highest dehydrogenase activity was observed in soil treated with vermicomposted rice straw (S_5) with a mean value of 29.60 µg TPF $g^{-1}day^{-1}$ and the lowest dehydrogenase activity of 16.92 µg TPF $g^{-1}day^{-1}$ was associated with absolute control (S_1), which was on par with soil treated with nutrients based on soil test data (17.22 µg TPF $g^{-1}day^{-1}$) *i.e.*, S_9.

Dehydrogenase activity varied significantly among the 36 treatment combinations after the incubation period. Soil treated with vermicomposted rice straw kept at 15 ºC (T_1S_5) showed highest dehydrogenase activity (31.46 µg TPF $g^{-1}day^{-1}$) and it was statistically on par with vermicomposted rice straw treated soil kept at 25 ºC *i.e.*, T_2S_5 (31.20 µg TPF $g^{-1}day^{-1}$). The lowest dehydrogenase activity was observed in the treatment combination T_4S_1 (15.92 µg TPF $g^{-1}day^{-1}$) and it was statistically on par with T_4S_9 (16.08 µg TPF $g^{-1}day^{-1}$), T_3S_1 (16.88 µg TPF $g^{-1}day^{-1}$), T_3S_9 (17.11 µg TPF $g^{-1}day^{-1}$), and T_2S_1 (17.27 µg TPF $g^{-1}day^{-1}$).

Table 4.9: Dehydrogenase activity after incubation experiment

Treatments	**Dehydrogenase activity (µg TPF $g^{-1}day^{-1}$)**				
	T_1(15 ºC)	T_2 (25 ºC)	T_3 (35 ºC)	T_4 (45 ºC)	Mean (S)
S_1 (Absolute control)	17.62	17.27	16.88	15.92	16.92
S_2 (Soil+ RH)	21.06	20.98	20.61	17.80	20.11
S_3 (Soil+ RS)	22.47	22.26	21.82	19.07	21.41
S_4 (Soil+ VRH)	29.23	29.12	28.47	25.48	28.08
S_5 (Soil+ VRS)	31.46	31.20	29.43	26.31	29.60
S_6 (Soil+ RHB)	24.72	24.51	24.38	24.00	24.40
S_7 (Soil+ RSB)	24.82	24.31	24.63	24.03	24.45
S_8 (Soil+ FYM)	29.21	28.80	28.13	24.56	27.68
S_9 (Soil+ Nutrients)	17.97	17.70	17.11	16.08	17.22
Mean (T)	24.28	24.02	23.50	21.47	
CD (0.05)	0.48*				0.73**
	1.45***				

CD (0.05)* : CD for comparing different temperatures (15, 25, 35 and 45 ºC)
CD (0.05)** : CD for comparing the sources
CD (0.05)***:CD for comparing the effect of sources under different temperature (interaction)

4.2.3. Microbial enumeration

The enumeration of soil microflora *viz*., bacteria, actinomycetes, and fungi was carried out before and after incubation experiment.

4.2.3.1. Microbial enumeration before incubation experiment

The results of microbial population obtained before the start of incubation experiment are furnished in Table 4.10. Statistically significant difference existed in the population of bacteria among the treatments. Bacterial population varied from 58.10 x 10^6 cfu g^{-1}soil to 64.25 x 10^6 cfu g^{-1}soil. Statistically highest bacterial population was observed in the soil treated with FYM (64.25 x 10^6 cfu g^{-1}soil). No significant difference was observed among the treatments in the population of actinomycetes and fungi before the commencement of incubation experiment.

Table 4.10: Microbial population before incubation experiment

Treatments	**Bacteria (x10^{6} cfu g^{-1}soil)**	**Actinomycetes (x10^{3} cfu g^{-1}soil)**	**Fungi (x10^{4} cfu g^{-1}soil)**
Absolute control	58.10^{c}	6.30	5.70
Soil+ RH	58.24^{c}	6.70	5.70
Soil+ RS	58.24^{c}	6.70	5.70
Soil+ VRH	61.82^{b}	7.00	5.80
Soil+ VRS	62.54^{b}	7.30	5.80
Soil+ RHB	58.24^{c}	6.70	5.70
Soil+ RSB	58.24^{c}	6.70	5.70
Soil+ FYM	64.25^{a}	7.00	5.80
Soil+ Nutrients	58.20^{c}	6.30	5.70
CD (0.05)	1.16	NS	NS

4.2.3.2. Microbial enumeration after incubation experiment

4.2.3.2.1. Bacterial population after incubation experiment

The data on bacterial population at different treatments under 15, 25, 35, and 45 ºC temperature after 110 days of incubation period are shown in Table 4.11.

Table 4.11 : Bacterial population after incubation experiment

Treatments	**Bacterial population (x10^{6} cfu g^{-1}soil)**				
	T$_1$(15 ºC)	T$_2$ (25 ºC)	T$_3$ (35 ºC)	T$_4$ (45 ºC)	Mean (S)
S$_1$ (Absolute control)	42.51	42.02	41.73	40.57	41.71
S$_2$ (Soil+ RH)	47.38	46.88	46.59	45.43	46.57
S$_3$ (Soil+ RS)	48.06	47.56	47.27	46.10	47.25
S$_4$ (Soil+ VRH)	57.13	56.66	56.35	55.15	56.32
S$_5$ (Soil+ VRS)	58.69	58.22	57.91	56.66	57.87
S$_6$ (Soil+ RHB)	55.40	54.90	54.61	53.44	54.59
S$_7$ (Soil+ RSB)	55.54	55.04	54.75	53.58	54.73
S$_8$ (Soil+ FYM)	55.81	55.36	55.04	53.75	54.99
S$_9$ (Soil+ Nutrients)	42.52	42.13	41.83	40.67	41.79
Mean (T)	51.45	50.97	50.68	49.84	
CD (0.05)	0.41*				0.62**
	1.23***				

CD (0.05)* : CD for comparing different temperatures (15, 25, 35 and 45 ºC)
CD (0.05)** : CD for comparing the treatment sources
CD (0.05)***: CD for comparing the effect of treatments under different temperatures (interaction)

The bacterial population showed a reduction after incubating soil for a period of 110 days as against the value before incubation.

Analysis of data on bacterial population showed significant variation between the different temperatures (15, 25, 35, and 45 ºC) after 110 days of incubation period with highest at T_1 (15 º C) with a mean value of 51.45 x10^6 cfu g^{-1}soil and lowest at T_4 (45 ºC) with a mean value of 49.84 x10^6 cfu g^{-1}soil.

Among the different treatments studied, higher bacterial population was observed in soil treated with vermicomposted rice straw (S_5) with a mean value of 57.87 x10^6 cfu g^{-1}soil and the lower was noted in absolute control with a mean value of 41.71 x10^6 cfu g^{-1}soil and it was on par with soil treated with nutrients based on soil test data (S_9) registering a mean value of 41.79 x10^6 cfu g^{-1}soil after the incubation period.

Among the 36 treatment combinations (interaction effect) after incubation period, bacterial population was found to be highest in T_1S_5 (58.69 x10^6 cfu g^{-1}soil) *i.e.*, soil treated with vermicomposted rice straw in 15 ºC, and it was statistically on par with T_2S_5 (58.22 x10^6 cfu g^{-1}soil) *i.e.*, soil treated with vermicomposted rice straw at 25 ºC and T_3S_5 (57.91 x10^6 cfu g^{-1}soil) *i.e.*, soil treated with vermicomposted rice straw at 35 ºC. The lowest bacterial population was noticed in T_4S_1 *i.e.*, absolute control at 45 ºC (40.57 x10^6 cfu g^{-1}soil) which was on par with T_4S_9 *i.e.*, soil test based nutrient recommendation kept at 45 ºC (40.67 x10^6 cfu g^{-1}soil) and T_3S_1 *i.e.*, absolute control in 35 ºC (41.73 x10^6 cfu g^{-1}soil).

4.2.3.2.2. Actinomycetes population after incubation experiment

Effects of treatments on actinomycetes population are presented in Table 4.12. Actinomycetes population got declined after 110 days of incubation period compared to the population before the beginning of incubation experiment.

Significant variation was observed in the population of actinomycetes under different temperatures. The actinomycetes population followed a decreasing trend with increase in temperature with lowest mean value at 45 ºC (4.64 x10^3 cfu g^{-1}soil) and highest in 15 ºC (6.22 x10^3 cfu g^{-1}soil).

Table 4.12: Population of actinomycetes after incubation experiment

Treatments	Actinomycetes population (x10^3 cfu g^{-1}soil)				
	T_1(15 ºC)	T_2 (25 ºC)	T_3 (35 ºC)	T_4 (45 ºC)	Mean (S)
S_1 (Absolute control)	5.33	4.67	4.33	3.80	4.53
S_2 (Soil+ RH)	6.00	5.33	5.00	4.43	5.19
S_3 (Soil+ RS)	6.33	5.67	5.30	4.43	5.43
S_4 (Soil+ VRH)	7.00	6.67	6.43	5.82	6.48
S_5 (Soil+ VRS)	7.00	7.00	6.45	6.33	6.69
S_6 (Soil+ RHB)	6.33	5.00	4.33	4.00	4.92
S_7 (Soil+ RSB)	6.33	5.40	4.33	3.80	4.97
S_8 (Soil+ FYM)	6.33	6.00	6.00	5.33	5.92
S_9 (Soil+ Nutrients)	5.33	4.80	4.33	3.80	4.57
Mean (T)	6.22	5.62	5.17	4.64	
CD (0.05)	0.11*				0.16**
	0.32***				

CD (0.05)* : CD for comparing different temperatures (15, 25, 35 and 45 ºC)
CD (0.05)** : CD for comparing the treatment sources
CD (0.05)***: CD for comparing the effect of treatments under different temperatures (interaction)

Table 4.13: Fungal population after incubation experiment

Treatments	Fungal population (x10^4 cfu g^{-1}soil)				
	T_1(15 ºC)	T_2 (25 ºC)	T_3 (35 ºC)	T_4 (45 ºC)	Mean (S)
S_1 (Absolute control)	3.00	1.70	0.70	0.20	1.40
S_2 (Soil+ RH)	4.00	2.60	0.90	0.50	2.00
S_3 (Soil+ RS)	4.00	3.00	1.40	0.70	2.28
S_4 (Soil+ VRH)	4.50	3.43	2.20	1.30	2.86
S_5 (Soil+ VRS)	4.50	3.40	3.00	1.80	3.18
S_6 (Soil+ RHB)	4.20	3.20	1.50	0.80	2.43
S_7 (Soil+ RSB)	4.20	3.20	1.60	0.80	2.45
S_8 (Soil+ FYM)	4.50	3.40	2.10	0.90	2.73
S_9 (Soil+ Nutrients)	3.00	1.70	0.70	0.20	1.40
Mean (T)	3.99	2.85	1.57	0.80	
CD (0.05)	0.14*				0.20**
	0.40***				

CD (0.05)* : CD for comparing different temperatures (15, 25, 35 and 45 ºC)
CD (0.05)** : CD for comparing the treatment sources
CD (0.05)***: CD for comparing the effect of treatments under different temperatures (interaction)

After the 110 days of incubation period, significant variation in actinomycetes population was observed among the different treatments with highest mean value of population observed in soil treated with vermicomposted rice straw (6.69 x10^3 cfu g^{-1}soil) and lowest in absolute control (4.53 x10^3 cfu g^{-1}soil) and it was statistically on par with soil treated with nutrients based on soil test data (4.57 x10^3 cfu g^{-1}soil).

Actinomycetes population showed significant variation among the different treatment combinations. The highest population of 7.00 x10^3 cfu g^{-1} soil was observed in T_1S_5 (vermicomposted rice straw treated soil under 15 ºC), T_1S_4 (vermicomposted rice husk treated soil under 15 ºC), and T_2S_5 (vermicomposted rice straw treated soil under 25 ºC). The lowest population of 3.80 x10^3 cfu g^{-1}soil was shown by T_4S_1 (absolute control at 45 ºC), T_4S_7 (soil treated with rice straw biochar at 45 ºC), and T_4S_9 (soil test based nutrient recommendation at 45 ºC), which was on par with T_4S_6 with a population of 4.00 x10^3 cfu g^{-1}soil (soil treated with rice husk biochar at 45 ºC).

4.2.3.2.3. Fungal population after incubation experiment

The data on fungal population observed after 110 days of incubation period are shown in Table 4.13.

Analysis of data on fungal population showed significant variation between the different temperatures *viz*., 15, 25, 35, and 45 ºC. Statistically the highest population mean (3.99 x10^4 cfu g^{-1}soil) was observed in T_1 (15 ºC) and lowest (0.80 x10^4 cfu g^{-1}soil) in T_4 (45 ºC).

Among the nine sources studied after incubation period, S_5 (soil treated with vermicomposted rice straw) recorded significantly higher fungal population mean (3.18 x10^4 cfu g^{-1}soil). The lowest population mean of 1.40 x10^4 cfu g^{-1}soil was observed in S_1 (absolute control) and S_9 (soil treated with nutrients based on soil test data).

Among the different treatment combinations studied, higher fungal population of 4.50 x 10^4 cfu g^{-1}soil was observed in T_1S_4, T_1S_5 and T_1S_8 and it was found to be statistically on par with fungal population in T_1S_6 and T_1S_7 with a population of 4.20 x10^4 cfu g^{-1}soil. The lowest fungal population of 0.20 x10^4 cfu g^{-1}soil was observed in T_4S_1 and T_4S_9 which were statistically on par with T_4S_2 having a population 0.50 x10^4 cfu g^{-1}soil.

4.2.4. Carbon fractions

The fractions of carbon contained in the samples before and after incubation are given in Table 4.14-4.19.

4.2.4.1. Carbon fractions before incubation experiment

The fractions of carbon *viz*., water soluble carbon (WSC), hot water extractable carbon (HWEC), microbial biomass carbon (MBC), permanganate oxidizable carbon (POXC), and total carbon (TC) just before the start of incubation experiment varied from 84.68 to 86.61mg kg^{-1}, 435.26 to 448.40 mg kg^{-1}, 112.83 to 114.68 mg kg^{-1}, 1448.42 to 1468.21 mg kg^{-1}, and 1.00 to 1.16 per cent, respectively (Table 4.14). Statistically no significant difference was observed among the various treatments in the fractions of carbon such as WSC, HWEC, MBC, and POXC.

Total carbon varied significantly among the treatments with highest value of 1.16 per cent recorded in soils treated with rice husk biochar and rice straw biochar and it was statistically on par with soils treated with vermicomposted rice straw (1.14 %), vermicomposted rice husk (1.14 %) and FYM (1.14 %). Total carbon was lowest (1.00 %) in absolute control and also in soils treated with nutrients.

4.2.4.1. Carbon fractions after incubation experiment

4.2.4.1.1. Water soluble carbon (WSC)

Water soluble carbon showed an increase in all the treatment combinations after the incubation experiment showing significant variations among temperatures, sources, and treatment combinations (Table 4.15).

The water soluble carbon showed an increase with rise in temperature and statistically higher mean value was observed in 45 ºC treated soils (109.36 mg kg^{-1}) and lowest in 15 ºC (94.27 mg kg^{-1}). Soils treated with vermicomposted rice straw (S_5) exhibited highest quantity of WSC (116.26 mg kg^{-1}) as against the absolute control (S_1) with 93.75 mg kg^{-1} WSC and it was found to be statistically on par with soil treated with nutrients based on soil test data with mean value of 94.28 mg kg^{-1} (S_9).

Table 4.14: Fractions of carbon before incubation

Treatments	WSC ($mgkg^{-1}$)	HWEC ($mgkg^{-1}$)	MBC ($mgkg^{-1}$)	POXC ($mgkg^{-1}$)	TC (%)
Absolute control	84.68	435.26	112.83	1448.42	1.00^c
Soil+ RH	84.68	435.26	112.83	1448.42	1.07^b
Soil+ RS	84.68	435.26	112.83	1448.42	1.07^b
Soil+ VRH	86.61	448.40	112.83	1455.34	1.14^a
Soil+ VRS	86.61	448.40	114.68	1468.21	1.14^a
Soil+ RHB	84.68	448.40	112.83	1462.83	1.16^a
Soil+ RSB	84.68	448.40	112.83	1462.83	1.16^a
Soil+ FYM	86.61	448.40	114.68	1455.34	1.14^a
Soil+ Nutrients	84.68	435.26	112.83	1448.42	1.00^c
CD (0.05)	NS	NS	NS	NS	0.02

Among the treatment combinations studied, highest WSC was obtained in T_4S_5 (133.32 mg kg^{-1}). The lowest WSC was obtained in the treatment combination T_1S_1 (89.68 mg kg^{-1}) and it was on par with T_1S_9 (90.08 mg kg^{-1}), T_1S_2 (90.48 mg kg^{-1}), T_1S_3 (91.18 mg kg^{-1}), and T_1S_6 (91.69 mg kg^{-1}).

4.2.4.1.2. Hot water extractable carbon (HWEC)

Hot water extractable carbon differed significantly among different temperatures, sources and treatment combinations (Table 4.16).

Vermicompost treated soil (S_5) recorded highest content of HWEC (461.09 mg kg^{-1}) whereas absolute control recorded the lowest (441.57 mg kg^{-1}) which was on par with S_9 (441.90 mg kg^{-1}) and S_2 (442.35 mg kg^{-1}).

Among the different temperatures studied, soils kept at T_4 recorded significantly highest HWEC (455.90 mg kg^{-1}) in comparison to T_1 that recorded the lowest (446.67 mg kg^{-1}).

Among the treatment combinations, T_4S_5 recorded highest HWEC (466.36 mg kg^{-1}). The lowest HWEC carbon was recorded in T_1S_1 (437.27 mg kg^{-1}), T_1S_9 (437.50 mg kg^{-1}), T_1S_2 (438.08 mg kg^{-1}), and T_1S_3 (438.66 mg kg^{-1}).

4.2.4.1.3. Microbial biomass carbon (MBC)

The microbial biomass carbon differed significantly among the different temperatures, sources and treatment combinations when studied after incubation period (Table 4.17).

Among the nine sources, S_5 recorded highest MBC with a mean value 132.44 mg kg^{-1}. The lowest mean value was observed in S_1 (97.04 mg kg^{-1}) which was statistically on par with S_9 (97.34 mg kg^{-1}).

Temperature had a significant effect on MBC. The microbial biomass carbon was lowest in soils treated at higher temperatures for a long time than the soil kept in lower temperature. The highest MBC was found in soils treated at 15 ºC (116.46 mg kg^{-1}) and lowest in 45 ºC with a mean value of 106.44 mg kg^{-1}.

Among the different treatment combinations studied, highest MBC was observed in T_1S_5 (142.80 mg kg^{-1}) and lowest in T_4S_1 (87.97 mg kg^{-1}) which was on par with T_4S_9 (88.01 mg kg^{-1}).

Table 4.15: Water soluble carbon (WSC) after incubation experiment

Treatments	WSC (mgkg^{-1})				
	T_1(15 ºC)	T_2 (25 ºC)	T_3 (35 ºC)	T_4 (45 ºC)	Mean (S)
S_1 (Absolute control)	89.68	92.67	94.68	97.98	93.75
S_2 (Soil+ RH)	90.48	94.00	95.00	102.08	95.39
S_3 (Soil+ RS)	91.18	94.48	97.58	104.73	96.99
S_4 (Soil+ VRH)	100.13	102.89	107.03	119.24	107.32
S_5 (Soil+ VRS)	104.47	109.06	118.17	133.32	116.26
S_6 (Soil+ RHB)	91.69	94.98	98.08	106.54	97.82
S_7 (Soil+ RSB)	91.98	95.28	98.57	107.15	98.25
S_8 (Soil+ FYM)	98.71	101.93	105.15	114.73	105.13
S_9 (Soil+ Nutrients)	90.08	93.38	95.18	98.48	94.28
Mean (T)	94.27	97.63	101.05	109.36	
CD (0.05)	0.69*				1.04**
	2.08***				

CD (0.05)* : CD for comparing different temperatures (15, 25, 35 and 45 ºC)
CD (0.05)** : CD for comparing the treatment sources
CD (0.05)***: CD for comparing the effect of treatments under different temperatures (interaction)

Table 4.16: Hot water extractable carbon (HWEC) after incubation experiment

Treatments	HWEC (mgkg^{-1})				
	T_1(15 ºC)	T_2 (25 ºC)	T_3 (35 ºC)	T_4 (45 ºC)	Mean (S)
S_1 (Absolute control)	437.27	440.26	443.31	445.43	441.57
S_2 (Soil+ RH)	438.08	441.08	444.07	446.16	442.35
S_3 (Soil+ RS)	438.66	441.76	445.20	448.10	443.43
S_4 (Soil+ VRH)	454.72	457.59	461.24	463.64	459.30
S_5 (Soil+ VRS)	455.70	458.96	463.32	466.36	461.09
S_6 (Soil+ RHB)	452.20	455.48	459.04	462.15	457.22
S_7 (Soil+ RSB)	452.30	455.50	458.92	462.22	457.24
S_8 (Soil+ FYM)	453.60	457.36	460.53	463.25	458.69
S_9 (Soil+ Nutrients)	437.50	440.62	443.67	445.80	441.90
Mean (T)	446.67	449.85	453.26	455.90	
CD (0.05)	0.60*				0.89**
	1.79***				

CD (0.05)* : CD for comparing different temperatures (15, 25, 35 and 45 ºC)
CD (0.05)** : CD for comparing the treatment sources
CD (0.05)***: CD for comparing the effect of treatments under different temperature (interaction)

Table 4.17: Microbial biomass carbon (MBC) after incubation experiment

Treatments	MBC (mgkg^{-1})				
	T_1(15 ºC)	T_2 (25 ºC)	T_3 (35 ºC)	T_4 (45 ºC)	Mean (S)
S_1 (Absolute control)	103.66	99.91	96.60	87.97	97.04
S_2 (Soil+ RH)	106.87	105.20	103.71	100.75	104.13
S_3 (Soil+ RS)	107.97	106.45	104.42	102.71	105.39
S_4 (Soil+ VRH)	130.65	126.91	123.06	119.95	125.14
S_5 (Soil+ VRS)	142.80	132.85	129.32	124.80	132.44
S_6 (Soil+ RHB)	110.67	109.69	108.68	107.81	109.21
S_7 (Soil+ RSB)	110.66	109.67	108.68	107.41	109.11
S_8 (Soil+ FYM)	130.11	126.40	122.84	118.55	124.48
S_9 (Soil+ Nutrients)	104.71	99.97	96.67	88.01	97.34
Mean (T)	116.46	113.01	110.44	106.44	
CD (0.05)	0.36*				0.53**
	1.07***				

CD (0.05)* : CD for comparing different temperatures (15, 25, 35 and 45 ºC)
CD (0.05)** : CD for comparing the treatment sources
CD (0.05)***: CD for comparing the effect of treatments under different temperatures (interaction)

4.2.4.1.4. Permanganate oxidizable carbon (POXC)

Permanganate oxidizable carbon was found decrease after incubation. Statistically significant variation was noticeable among the different temperatures, sources and treatment combinations studied after the incubation period of 110 days (Table 4.18). The highest POXC was recorded in S_5 (1390.60 mg kg^{-1}) after the incubation experiment. The lowest POXC was observed in S_1 (1124.09 mg kg^{-1}) and it was on par with S_9 (1125.83 mg kg^{-1}).

Permanganate oxidizable carbon differed significantly among the different temperatures studied. The highest POXC was noted in T_1 (1340.80 mg kg^{-1}) and lowest in T_4 (1065.56 mg kg^{-1}).

Among the treatment combinations studied, T_1S_5 recorded highest POXC (1426.83 mg kg^{-1}). The lowest POXC was recorded by T_4S_1 (912.30 mg kg^{-1}) and it was found to be statistically on par with T_4S_9 (914.25 mg kg^{-1}).

4.2.4.1.5. Total carbon (TC)

The data on total carbon after 110 days of incubation period are presented in Table 4.19. Total carbon was found to decrease after the incubation compared to total carbon before the commencement of incubation. Statistically significant differences could be noted among the different temperatures, sources and treatment combinations studied.

Total carbon was found to be lowest in soils treated at 45 ^{o}C (T_4) for 110 days with a mean value of 1.03 per cent. The highest quantity was noted in soils treated at 15 ^{o}C (T_1) with a value of 1.08 per cent and it was statistically on par with carbon content in soils treated at 25 ^{o}C (T_2) with 1.07 per cent carbon.

After the incubation period, biochar treated soils (S_6 and S_7) recorded highest quantity of total carbon (1.14%). However it was the lowest in both absolute control and in soil treated with nutrients registering a mean value of 0.92 per cent.

Among the 36 treatment combinations studied, significant variation was observed in carbon content with highest value of 1.15 per cent obtained in T_1S_6 and T_1S_7 which was found to be statistically on par with T_2S_6 (1.14 %), T_2S_7 (1.14 %), T_1S_4 (1.13 %), T_1S_5 (1.13 %), T_3S_6 (1.13 %), and T_3S_7 (1.13 %). Total carbon was found to be lowest in T_4S_1 and T_4S_9 with a content of 0.92 per cent.

Table 4.18: Permanganate oxidizable carbon (POXC) after incubation experiment

Treatments	POXC (mgkg^{-1})				
	T_1(15 ºC)	T_2 (25 ºC)	T_3 (35 ºC)	T_4 (45 ºC)	Mean (S)
S_1 (Absolute control)	1290.42	1202.42	1091.22	912.30	1124.09
S_2 (Soil+ RH)	1298.42	1218.42	1101.75	928.42	1136.75
S_3 (Soil+ RS)	1300.42	1226.42	1102.42	929.42	1139.67
S_4 (Soil+ VRH)	1414.83	1402.83	1373.83	1327.83	1379.83
S_5 (Soil+ VRS)	1426.83	1408.83	1385.42	1341.33	1390.60
S_6 (Soil+ RHB)	1330.34	1266.84	1170.26	1028.21	1198.91
S_7 (Soil+ RSB)	1345.34	1290.34	1205.84	1080.84	1230.59
S_8 (Soil+ FYM)	1370.22	1321.21	1239.71	1127.46	1264.65
S_9 (Soil+ Nutrients)	1290.42	1206.42	1092.22	914.25	1125.83
Mean (T)	1340.80	1282.64	1195.85	1065.56	
CD (0.05)	2.51*				3.77**
	7.54***				

CD (0.05)* : CD for comparing different temperatures (15, 25, 35 and 45 ºC)
CD (0.05)** : CD for comparing the treatment sources
CD (0.05)***: CD for comparing the effect of treatments under different temperature (interaction)

Table 4.19: Total carbon (TC) after incubation experiment

Treatments	TC (%)				
	T_1(15 ºC)	T_2 (25 ºC)	T_3 (35 ºC)	T_4 (45 ºC)	Mean (S)
S_1 (Absolute control)	0.97	0.94	0.92	0.86	0.92
S_2 (Soil+ RH)	1.06	1.05	1.05	1.02	1.05
S_3 (Soil+ RS)	1.06	1.06	1.04	1.02	1.05
S_4 (Soil+ VRH)	1.13	1.12	1.10	1.08	1.11
S_5 (Soil+ VRS)	1.13	1.12	1.10	1.09	1.11
S_6 (Soil+ RHB)	1.15	1.14	1.13	1.13	1.14
S_7 (Soil+ RSB)	1.15	1.14	1.13	1.13	1.14
S_8 (Soil+ FYM)	1.12	1.12	1.10	1.08	1.11
S_9 (Soil+ Nutrients)	0.96	0.94	0.92	0.86	0.92
Mean (T)	1.08	1.07	1.05	1.03	
CD (0.05)	0.01*				0.01**
	0.02***				

CD (0.05)* : CD for comparing different temperatures (15, 25, 35 and 45 ºC)
CD (0.05)** : CD for comparing the treatment sources
CD (0.05)***: CD for comparing the effect of treatments under different temperatures (interaction)

4.3. FIELD EXPERIMENT

A field experiment was conducted to evaluate the efficacy of rice residues and their products in lowland rice.

4.3.1. Monitoring Eh and pH

The redox potential (Eh) and pH was monitored at weekly intervals after transplanting till the harvest of the crop and the data are presented in Table 4.20 and 4.21.

4.3.1.1. Eh

Redox potential (Eh) is a measure of the tendency of a given system either to oxidise or reduce substances. Any chemical reaction which involves the exchange of electrons will be influenced by Eh. The data on redox potential monitored from 10 cm depth after transplanting till two weeks before harvest of the crop are presented in Table 4.20.

In the present study, redox potential followed an increasing trend in all the treatments upto four weeks after transplanting followed by a decrease thereafter till 13 weeks after transplanting. The highest Eh of 176.8 mV was showed by absolute control (T_1) at one week after transplanting and lower Eh of 126.4 mV was recorded by soil added with vermicomposted rice straw (T_5). Similar trend was followed after 13 weeks of transplanting with higher Eh in absolute control (T_1) with a value of 144.3 mV and lower Eh of 80.4 mV in soil treated with vermicomposted rice straw (T_5).

4.3.1.2. Soil pH

Soil reaction or pH is an important electro-chemical property that decides the availability of various nutrients. After one week of transplanting, higher pH was recorded by T_7 (6.9) followed by T_6 (6.8), T_5 (6.3), T_4 and T_9 (6.2), T_3 (6.1), T_2 (5.9), T_8 (5.8) and finally T_1 (5.4). After 15 weeks, the soil pH was found decreased and it followed the order: T_7=T_6 (6.6) > T_5 (6.0) > T_2 (5.7) > T_3=T_4 (5.6) > T_9 (5.5) > T_8 (5.4) > T_1 (4.3). The data indicated (Table 4.21) that the pH of T_1 (absolute control) was lower compared to the all other treatments after transplanting till harvest of rice. Generally, a decreasing trend was observed in case of soil pH. Whereas, at four weeks after transplanting, there was a slight increase in pH in all the treatments except T_1.

Table 4.20: Eh (mV) at weekly intervals

WAT	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9
1	166.0	135.1	138.1	142.5	130.7	153.8	153.1	147.3	145.7
2	164.7	133.7	136.8	141.2	129.4	152.5	151.8	146.0	144.4
3	163.7	132.6	135.6	140.0	128.2	151.3	150.6	144.8	143.2
4	174.1	143.3	148.2	150.3	138.2	160.2	159.8	154.1	150.3
5	173.5	140.2	144.1	148.3	136.1	159.3	158.2	152.8	148.6
6	166.5	138.8	140.8	144.2	129.3	155.2	154.6	150.1	144.7
7	160.4	130.3	136.7	138.4	118.1	150.2	149.3	148.6	140.4
8	158.4	128.8	130.8	135.8	106.2	148.2	145.3	148.2	136.2
9	157.6	120.5	126.2	130.8	98.4	136.8	134.2	138.6	131.7
10	154.5	118.4	120.1	125.2	87.8	135.4	132.8	132.3	126.4
11	152.8	114.2	114.6	120.0	80.4	132.1	131.5	129.4	122.3
12	150.3	111.7	112.1	117.5	76.0	129.6	129.0	126.9	119.8
13	148.44	109.84	110.24	115.64	74.25	127.74	127.14	125.04	117.94
Mean	160.84	127.50	130.33	134.60	110.23	145.56	144.41	141.86	136.28
CD (0.05)	4.45								

WAT: Weeks after transplanting

Table 4.21: Soil pH at weekly intervals

WAT	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9
1	5.4	5.9	6.1	6.2	6.3	6.8	6.9	5.8	6.2
2	5.4	5.9	6.1	6.2	6.3	6.8	6.9	5.8	6.2
3	5.3	5.9	6.1	6.2	6.3	6.8	6.9	5.7	6.1
4	5.2	5.8	6.0	6.1	6.2	6.7	6.8	5.6	6.0
5	5.1	6.0	6.1	6.2	6.3	6.9	6.9	5.7	6.1
6	5.0	6.1	6.2	6.3	6.4	6.9	6.9	5.8	6.2
7	4.9	6.1	6.2	6.3	6.4	6.9	6.9	5.8	6.2
8	4.9	6.0	6.1	6.1	6.3	6.8	6.8	5.7	6.2
9	4.8	6.0	6.0	6.0	6.3	6.8	6.8	5.7	6.1
10	4.8	6.0	6.0	5.9	6.2	6.7	6.8	5.6	6.0
11	4.7	5.9	5.9	5.8	6.2	6.7	6.7	5.6	5.8
12	4.7	5.9	5.8	5.8	6.1	6.7	6.7	5.5	5.7
13	4.6	5.8	5.7	5.7	6.1	6.6	6.7	5.5	5.7
14	4.5	5.8	5.7	5.7	6.0	6.6	6.6	5.4	5.6
15	4.3	5.7	5.6	5.6	6.0	6.6	6.6	5.4	5.5
Mean	4.91	5.92	5.97	6.01	6.23	6.75	6.79	5.64	5.97
CD (0.05)	0.01								

WAT: Weeks after transplanting

4.3.2. Soil characteristics

The physical and chemical characteristics of soil were analysed before and after the experiment to gather information on the effect of rice residues and their products such as vermicompost and biochar.

4.3.2.1. Soil characteristics before field experiment

4.3.2.1.1. Physical properties

The physical properties of the soil such as bulk density, particle density, porosity, MWD, and water holding capacity were analysed at the beginning of experiment to have basic information of the experimental soils (Table 4.22).

The bulk density, particle density, porosity, MWD, and water holding capacity of the soil before commencement of field experiment were 1.34 Mg m^{-3}, 2.33 Mg m^{-3}, 42.49 per cent, 0.97mm, and 38.60 per cent, respectively.

Table 4.22: Physical properties of soil before field experiment

Physical properties	Value
Bulk density (Mg m^{-3})	1.34
Particle density (Mg m^{-3})	2.33
Porosity (%)	42.49
MWD (mm)	0.97
Water holding capacity (%)	38.60

4.3.2.1.2. Chemical properties

The chemical properties of the soil *viz.*, organic carbon, available nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, manganese, copper, zinc, boron, and silicon were analysed just before the start of field experiment and the data are presented in Table 4.23.

The data shows that the content of organic carbon, available nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, manganese, copper, zinc, boron, and silicon in soil were 0.96 per cent, 312.89 kg ha^{-1}, 16.58 kg ha^{-1}, 228.16 kg ha^{-1}, 112.53 mg kg^{-1}, 26.82

mg kg^{-1}, 3.16 mg kg^{-1}, 152.34 mg kg^{-1}, 17.24 mg kg^{-1}, 4.08 mg kg^{-1}, 3.54 mg kg^{-1}, 0.38 mg kg^{-1}, and 17.23 kg ha^{-1}, respectively.

Table 4.23: Chemical properties of soil before field experiment

Chemical properties		Value
Organic carbon	%	0.96
Nitrogen	kg ha^{-1}	312.89
Phosphorus		16.58
Potassium		228.16
Calcium	mg kg^{-1}	112.53
Magnesium		26.82
Sulphur		3.16
Iron		152.34
Manganese		17.24
Zinc		4.08
Copper		3.54
Boron		0.38
Silicon	kg ha^{-1}	17.23

4.3.2.2. Soil characteristics after field experiment

4.3.2.2.1. Physical properties

The physical properties of the soil such as bulk density, particle density, porosity, MWD, and water holding capacity were analysed (Table 4.24) after the field experiment to know the efficacy of rice residues and their products on the physical properties of soil.

The application of various treatments had significant effect on altering soil bulk density. Highest bulk density was observed in T_1 (1.36 Mg m^{-3}) and lowest in T_6 and T_7 with bulk density 1.28 Mg m^{-3}.

Particle density was varied from 2.30 to 2.33 Mg m^{-3}. No significant difference was observed as a result of treatment application.

Porosity of soils varied from 41.63 to 45.06 per cent, with lowest in T_1 (absolute control) and highest in T_6 and T_7 (biochar amended soils).

Mean weight diameter (MWD) varied significantly among the treatments and highest MWD was observed in T_6 (1.40mm) which was on par with T_7 (1.37mm) and T_5 (1.36mm). The lowest MWD was recorded in T_1 (0.98mm).

The highest WHC was observed in biochar amended soil (T_6 and T_7). The application of soil test based nutrients along with rice husk biochar (T_6) resulted in 45.28 per cent WHC and it was on par with T_7 (soil test based nutrient recommendation + rice straw biochar) having 44.85 per cent WHC. The lowest WHC of 38.60 per cent was observed in T_1 (absolute control).

Table 4.24: Physical properties of soil after field experiment

Treatments	**Bulk density (Mg m^{-3})**	**Particle density (Mg m^{-3})**	**Porosity (%)**	**MWD (mm)**	**WHC (%)**
T_1	1.36^{a}	2.33	41.63^{e}	0.98^{e}	38.60^{f}
T_2	1.32^{bc}	2.30	43.35^{cd}	1.20^{cd}	43.28^{c}
T_3	1.31^{bcd}	2.31	43.64^{bcd}	1.28^{b}	42.86^{c}
T_4	1.31^{bcd}	2.31	43.78^{bc}	1.24^{bc}	43.12^{c}
T_5	1.30^{d}	2.30	44.21^{b}	1.36^{a}	44.23^{b}
T_6	1.28^{e}	2.31	45.06^{a}	1.40^{a}	45.28^{a}
T_7	1.28^{e}	2.31	45.06^{a}	1.37^{a}	44.85^{a}
T_8	1.33^{b}	2.31	42.92^{d}	1.14^{d}	41.08^{d}
T_9	1.32^{bc}	2.31	43.35^{cd}	1.18^{cd}	41.95^{e}
CD (0.05)	0.02	NS	0.74	0.08	0.58

4.3.2.2.2. Chemical properties

Organic carbon, available nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, manganese, copper, zinc, boron, and silicon were analysed after the field experiment to know the effect of treatments on chemical properties of soil and the data are furnished in Table 4.25.

Table 4.25: Effect of treatments on chemical properties

Treatments	**OC**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Si**
	%	**kg ha^{-1}**			**mg kg^{-1}**								**kg ha^{-1}**
T$_1$	0.85^{d} (8.5gkg^{-1})	278.36^{g}	14.28^{e}	217.62^{h}	98.64^{f}	24.35^{g}	2.86^{h}	148.50^{f}	16.83^{i}	4.02^{f}	2.12^{d}	0.36^{d}	16.87^{h}
T$_2$	1.07^{b} (10.7gkg^{-1})	347.43^{b}	20.78^{c}	268.64^{d}	112.45^{d}	26.83^{b}	3.12^{f}	158.28^{bc}	18.93^{d}	4.56^{b}	3.60^{a}	0.38^{cd}	16.88^{g}
T$_3$	1.00^{c} (10.0gkg^{-1})	320.81^{d}	22.43^{b}	252.47^{e}	110.32^{e}	26.45^{c}	3.10^{fg}	157.35^{c}	18.24^{e}	4.42^{c}	3.64^{a}	0.48^{a}	16.92^{g}
T$_4$	1.05^{b} (10.5gkg^{-1})	326.47^{c}	20.84^{c}	234.43^{g}	114.85^{c}	25.92^{de}	4.36^{b}	151.46^{d}	17.83^{f}	4.36^{cd}	3.64^{a}	0.48^{a}	22.86^{c}
T$_5$	1.12^{a} (11.2gkg^{-1})	364.68^{a}	24.86^{a}	302.68^{b}	120.34^{a}	27.17^{a}	4.85^{a}	162.13^{a}	19.72^{a}	4.80^{a}	3.65^{a}	0.48^{a}	29.48^{a}
T$_6$	1.13^{a} (11.3gkg^{-1})	285.48^{f}	17.37^{d}	248.21^{f}	114.47^{c}	25.86^{e}	3.96^{c}	151.45^{d}	17.56^{g}	4.30^{de}	3.58^{a}	0.44^{b}	28.10^{b}
T$_7$	1.13^{a} (11.3gkg^{-1})	286.12^{f}	17.32^{d}	326.23^{a}	115.82^{b}	26.12^{d}	3.88^{d}	158.84^{b}	19.36^{b}	4.53^{b}	3.45^{b}	0.44^{b}	28.00^{b}
T$_8$	0.97^{c} (9.7gkg^{-1})	286.87^{f}	16.82^{d}	232.54^{g}	112.86^{d}	25.62^{f}	3.08^{g}	150.23^{e}	17.02^{h}	4.28^{e}	2.86^{c}	0.40^{c}	17.22^{e}
T$_9$	1.00^{c} (10.0gkg^{-1})	312.93^{e}	16.80^{d}	282.14^{c}	115.63^{b}	26.08^{d}	3.26^{e}	158.51^{b}	19.21^{c}	4.38^{c}	3.38^{b}	0.40^{c}	17.45^{d}
CD (0.05)	0.04	2.40	1.56	2.38	0.61	0.21	0.03	1.14	0.02	0.07	0.09	0.03	0.09

Organic carbon varied from 0.85 to 1.13 per cent. Among the nine treatments studied, T_1 recorded lowest organic carbon (0.85 %). The treatments T_6 and T_7 were the highest with1.13 per cent organic carbon which was statistically on par with T_5 (1.12 %).

The effect of various treatments on soil nitrogen was studied after field experiment. The highest nitrogen content of 364.68 kg ha^{-1} was obtained in T_5 and the lowest in T_1 (278.36 kg ha^{-1}). The nitrogen content in various treatments followed the order: $T_5 > T_2 > T_4 > T_3 > T_9 > T_8 > T_6 > T_7 > T_1$. Even though the variation in nitrogen content was only slight in the treatments T_8, T_6, and T_7, they remained on par statistically.

After field experiment, the phosphorus content in the soils varied from 14.28 to 24.86 kg ha^{-1}. Phosphorus was found to be highest in T_5 (24.86 kg ha^{-1}) and lowest in T_1 (14.28 kg ha^{-1}).

Statistically significant variation was observed in potassium content of various treatments after field experiment and the potassium content of the treatments followed the order: $T_7 > T_5 > T_9 > T_2 > T_3 > T_6 > T_4 > T_8 > T_1$. The potassium content in T_7 was 326.23 kg $ha^{-1}$and it was 217.62 kg ha^{-1} in T_1.

The highest calcium content was observed in T_5 (120.34 mg kg^{-1}) and lowest in T_1 (98.64 mg kg^{-1}). The calcium content in various treatments followed the order: $T_5 > T_7 > T_9 > T_4 > T_6 > T_8 > T_2 > T_3 > T_1$. The calcium content in T_7 was statistically on par with T_9. Similarly, T_4 and T_6, T_8 and T_2 were also on par.

Among the various treatments studied, T_5 (27.17 mg kg^{-1}) recorded highest magnesium content whereas, T_1 (24.35 mg kg^{-1}) was the lowest. The magnesium content in the treatments was in the order of $T_5 > T_2 > T_3 > T_7 > T_9 > T_4 > T_6 > T_8 > T_1$, where T_7, T_9, and T_4 were statistically on par besides T_4 and T_6.

Significant variation was observed in sulphur content of various treatments after the field experiment. The highest sulphur content was observed in T_5 (4.85 mg kg^{-1}) and the lowest (2.86 mg kg^{-1}) in T_1. The sulphur content in various treatments followed the order: $T_5 > T_4 > T_6 > T_7 > T_9 > T_2 > T_3 > T_8 > T_1$. Treatments T_2 and T_3 as well as T_8 and T_3 were on par.

Iron content was highest in T_5 (162.13 mg kg^{-1}) and lowest in T_1 (148.50 mg kg^{-1}). The iron content in T_7, T_9, and T_2 were statistically on par. The treatments T_2 and T_3 were also on par with respect to iron content besides T_4 and T_6 are on par. Iron content in various treatments obeyed the order: $T_5 > T_7 > T_9 > T_2 > T_3 > T_4 > T_6 > T_8 > T_1$.

The content of manganese differed significantly among various treatments. The highest content was observed in T_5 (19.7 mg kg^{-1}) and the lowest in T_1 (16.83 mg kg^{-1}). The manganese content followed the order: $T_5 > T_7 > T_9 > T_2 > T_3 > T_4 > T_6 > T_8 > T_1$.

Zinc content was found to be highest in T_5 (4.80 mg kg^{-1}) and lowest in T_1 (4.02 mg kg^{-1}). Zinc content of the various treatments was in the order: $T_5 > T_2 > T_7 > T_3 > T_9 > T_4 > T_6 > T_8 > T_1$.

Boron content in soil after field experiment varied from 0.36 to 0.48 mg kg^{-1}. Boron content was 0.48 mg kg^{-1} in T_5, T_4, and T_3 and they are statistically higher than other treatments. The lowest boron content was observed in T_1 (0.36 mg kg^{-1}).

Copper content varied from 2.12 to 3.65 mg kg^{-1}with significantly highest in T_2 , T_3 ,T_4 ,T_5 ,T_6 and lowest in T_1.

Highest silicon content was observed in T_5 (29.48 kg ha^{-1}) and lowest was in T_1 (16.87 kg ha^{-1}).

4.3.3. Fractionation

Fractions of carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, and silicon were analysed at three stages of field experiment *viz*., before planting, at tillering, and at panicle initiation.

4.3.3.1. Carbon

4.3.3.1. 1. Carbon fractions before planting

Before planting, water soluble carbon (WSC) ranged from 84.72 to 94.26 mg kg^{-1} (Table 4.26). The lowest WSC was recorded in T_1 (absolute control) and the highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw).

The highest HWEC of 582.16 mg kg^{-1} was recorded in T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest of 440.18 mg kg^{-1} was recorded in T_1 (absolute control).

Table 4.26: Fractions of carbon before planting

Treatments	WSC	HWEC	MBC	POXC	TC
	mgkg^{-1}				(%)
T_1	84.72^{e}	440.18^{h}	120.12^{e}	1400.82^{f}	0.96^{d}
T_2	92.94^{b}	545.21^{e}	140.08^{b}	1530.18^{d}	1.14^{b}
T_3	92.86^{b}	548.32^{d}	140.92^{b}	1536.01^{d}	1.14^{b}
T_4	90.28^{c}	561.08^{b}	135.21^{c}	1620.75^{b}	1.16^{b}
T_5	94.26^{a}	582.16^{a}	150.35^{a}	1682.10^{a}	1.16^{b}
T_6	90.23^{c}	560.47^{bc}	128.86^{d}	1548.65^{d}	1.20^{a}
T_7	90.75^{c}	560.01^{c}	130.04^{d}	1585.90^{c}	1.20^{a}
T_8	85.10^{de}	531.42^{g}	120.56^{e}	1448.51^{e}	1.05^{c}
T_9	85.48^{d}	536.18^{f}	120.80^{e}	1460.38^{e}	1.05^{c}
CD (0.05)	0.71	0.86	1.50	26.62	0.03

The microbial biomass carbon (MBC) was observed to range from 120.12 to 150.35 mg kg^{-1}. The MBC recorded in T_1, T_8, and T_9 were on par and were significantly lower than that in other treatments. The highest MBC was obtained from T_5.

The permanganate oxidizable carbon (POXC) varied from 1400.82 to 1682.10 mgkg^{-1} with lowest in T_1 (absolute control) and highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw).

The total carbon was found to vary from 0.96 to 1.20 per cent. The total carbon content in T_6 (soil test based nutrient recommendation + rice husk biochar) and T_7 (soil test based nutrient recommendation + rice straw biochar) were on par and were significantly higher than that in other treatments. Absolute control (T_1) recorded the lowest fraction of total carbon.

4.3.3.1. 2. Carbon fractions at tillering

The WSC varied from 85.01 to 98.12 mg kg^{-1} (4.27). The content of WSC was lowest in T_1 and highest in T_5.

The HWEC content ranged from 436.17 to 560.01 mg kg^{-1} with lowest in T_1 and highest in T_5.

Table 4.27: Fractions of carbon at tillering

Treatments	WSC	HWEC	MBC	POXC	TOC
	mgkg^{-1}				%
T_1	85.01^{g}	436.17^{g}	148.06^{i}	1272.16^{g}	0.90^{f}
T_2	95.83^{b}	534.92^{d}	190.35^{c}	1418.21^{e}	1.12^{c}
T_3	95.54^{b}	534.10^{d}	192.84^{b}	1422.01^{e}	1.12^{c}
T_4	94.08^{c}	552.12^{c}	183.46^{d}	1508.12^{b}	1.12^{c}
T_5	98.12^{a}	560.01^{a}	212.50^{a}	1574.76^{a}	1.14^{b}
T_6	93.01^{d}	553.75^{b}	178.04^{f}	1436.12^{d}	1.19^{a}
T_7	93.21^{d}	553.04^{bc}	178.72^{e}	1475.55^{c}	1.19^{a}
T_8	87.12^{f}	526.72^{f}	165.56^{h}	1316.72^{f}	1.02^{e}
T_9	88.23^{e}	528.16^{g}	169.80^{g}	1324.85^{f}	1.04^{d}
CD (0.05)	0.73	1.43	0.10	12.29	0.01

Statistically significant difference was observed in MBC due to the application of treatments. The MBC ranged from 148.06 to 212.50 mg kg^{-1}and in various treatments it followed the order: $T_5 > T_3 > T_2 > T_4 > T_7 > T_6 > T_9 > T_8 > T_1$.

The values on POXC ranged from 1272.16 to 1574.76 mg kg^{-1} in different treatments. This fraction was highest in T_5 and lowest in T_1.

The total carbon content at tillering stage was found to vary from 0.90 to 1.19 per cent. The total carbon in T_7 (soil test based nutrient recommendation + rice straw biochar) and T_6 (soil test based nutrient recommendation + rice husk biochar) were identical and were significantly higher than that in other treatments.

4.3.3.1. 3. Carbon fractions at panicle initiation

Water soluble carbon (WSC) was observed to range from 85.24 to 115.32 mg kg^{-1} (Table 4.28). The lowest WSC was recorded in absolute control (T_1) and highest in soil receiving combined applications of soil test based nutrient recommendation and vermicomposted rice straw (T_5).

The highest HWEC of 464.21 mg kg^{-1} was recorded in T_5 *i.e.*, plots receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw and lowest of 376.17 mg kg^{-1} was recorded in T_1 *i.e.*, absolute control.

Table 4.28: Fractions of carbon at panicle initiation

Treatments	**WSC**	**HWEC**	**MBC**	**POXC**	**TOC**
	mg kg^{-1}				**%**
T_1	85.24^{h}	376.17^{e}	188.18^{h}	1135.08^{h}	0.86^{e}
T_2	107.80^{b}	438.86^{c}	256.01^{b}	1313.96^{e}	1.05^{bc}
T_3	107.02^{cd}	438.65^{c}	256.42^{b}	1327.74^{e}	1.05^{bc}
T_4	107.12^{c}	456.76^{b}	250.55^{c}	1412.25^{b}	1.08^{bc}
T_5	115.32^{a}	464.21^{a}	288.86^{a}	1488.76^{a}	1.10^{b}
T_6	106.35^{e}	456.57^{b}	242.72^{e}	1347.68^{d}	1.18^{a}
T_7	106.92^{d}	456.23^{b}	244.08^{d}	1386.32^{c}	1.18^{a}
T_8	92.16^{g}	424.08^{d}	220.84^{g}	1218.34^{g}	0.98^{d}
T_9	98.12^{f}	426.43^{d}	224.02^{f}	1240.65^{f}	1.02^{cd}
CD (0.05)	0.11	4.04	0.55	16.58	0.07

The MBC was observed to range from 188.18 to 288.86 mg kg^{-1}. The treatment T_5 (soil test based nutrient recommendation + vermicomposted rice straw) recorded highest MBC while T_1 (absolute control), the lowest.

The permanganate oxidizable carbon (POXC) in T_5 (1488.76 mg kg^{-1}) was found to be significantly higher than that in other treatments. Absolute control (T_1) registered the lowest value (1135.08 mg kg^{-1}) for POXC.

Total carbon content was found to vary from 0.86 to 1.18 per cent and was highest in T_7 and T_6 as against other treatments. The lowest value was recorded in T_1.

4.3.3.2. Nitrogen

4.3.3.2.1. Nitrogen fractions before planting

Before planting, the fraction of total hydrolysable-N content in different treatments ranged from 1520.62 mg kg^{-1} (T_1) to 2296.35 mg kg^{-1} (T_7). The total hydrolysable-N fraction recorded in T_7 was on par with T_6 and T_5 and was significantly higher than all other treatments (Table 4.29).

Table 4.29: Fractions of nitrogen before planting

Treatments	Total hydrolysable- N	Amino acid- N	Ammoniacal- N	Nitrate- N
	mg kg^{-1}			
T_1	2001.08^{d}	984.21^{i}	55.02^{h}	34.21^{e}
T_2	2138.84^{b}	1148.56^{e}	57.75^{ab}	37.84^{ab}
T_3	2146.71^{b}	1125.12^{f}	57.64^{b}	37.76^{ab}
T_4	2158.65^{b}	1388.96^{b}	56.82^{c}	37.12^{bc}
T_5	2274.84^{a}	1428.67^{a}	57.86^{a}	38.16^{a}
T_6	2285.10^{a}	1178.14^{d}	56.41^{e}	36.40^{c}
T_7	2296.35^{a}	1378.54^{c}	56.53^{d}	36.55^{c}
T_8	2056.10^{c}	1012.14^{h}	55.90^{f}	35.24^{d}
T_9	2078.55^{c}	1025.61^{g}	55.28^{g}	35.37^{d}
CD (0.05)	22.58	6.53	0.12	0.87

Amino acid-N fraction in treatments differed significantly and the content ranged from 984.21 to 1428.67 mg kg^{-1}. Treatments followed the order: $T_5 > T_4 > T_7 > T_6 > T_2 > T_3 > T_9 > T_8 > T_1$.

Ammoniacal-N content in treatments varied from 55.02 (T_1) to 57.86 mg kg^{-1} (T_5). The content of ammoniacal-N in T_5 was on par with T_2 and it was higher than other treatments.

The fraction of nitrate-N varied from 34.21 to 38.16 mg kg^{-1}. Nitrate-N fraction in T_5 was on par with T_2 (37.84 mg kg^{-1}) and T_3 (37.76 mg kg^{-1}) and it was higher than other treatments. The lowest fraction was recorded in T_1.

4.3.3.2. 1. Nitrogen fractions at tillering

At tillering stage, total hydrolysable-N in T_7 (2184.75 mg kg^{-1}) and T_6 (2162.87 mg kg^{-1}) was on par and it was highest than all other treatments (Table 4.30). Treatment T_1 (938.81 mg kg^{-1}) was lowest in terms of total hydrolysable-N.

The amino acid-N fraction in T_5 (1252.56 mg kg^{-1}) was significantly higher than that in all other treatments at tillering stage of rice. The treatments obeyed the order: $T_5 > T_4 > T_7 > T_6 > T_2 > T_3 > T_9 > T_8 > T_1$.

Table 4.30: Fractions of nitrogen at tillering

Treatments	Total hydrolysable- N	Amino acid- N	Ammoniacal- N	Nitrate- N
	mg kg^{-1}			
T_1	938.81^f	825.63^i	38.76^f	23.92^i
T_2	1896.23^c	948.36^e	52.13^a	31.75^b
T_3	1915.64^c	934.65^f	52.01^a	30.84^c
T_4	1935.94^c	1185.48^b	50.25^b	30.08^d
T_5	2081.53^b	1252.56^a	52.65^a	32.14^a
T_6	2162.87^a	986.40^d	48.68^c	28.16^f
T_7	2184.75^a	1128.94^c	48.92^c	28.72^e
T_8	1465.08^e	885.22^h	44.83^e	24.75^h
T_9	1518.35^d	905.10^g	46.34^d	24.91^g
CD (0.05)	45.79	7.19	0.75	0.11

Ammoniacal-N content of treatments ranged from 38.76 (T_1) to 52.65 mg kg^{-1} (T_5). The fraction of ammoniacal-N in T_5 was on par with T_2 (52.13 mg kg^{-1}) and T_3 (52.01mgkg^{-1}) and they were significantly higher than that in other treatments.

The nitrate-N content was significantly influenced by treatment application and it was highest in T_5 (32.14 mg kg^{-1}) and lowest in T_1 (23.92 mg kg^{-1}). Fraction of nitrate-N in various treatments followed the order: $T_5 > T_2 > T_3 > T_4 > T_7 > T_6 > T_9 > T_8 > T_1$.

4.3.3.2.1. Nitrogen fractions at panicle initiation

The total hydrolysable fraction of soil nitrogen estimated in the soils of treatment plots are presented in Table 4.31. Total hydrolysable-N was significantly influenced by treatment application and it followed the order: $T_7 > T_6 > T_5 > T_4 > T_2 > T_3 > T_9 > T_8 > T_1$. The higher content was recorded in T_7 (2168.06 mg kg^{-1}) and lowest in T_1 containing 821.96 mg kg^{-1} total hydrolysable-N.

The amino acid-N in treatments varied from 768.14 to 1248.51 mg kg^{-1} with highest in T_5 (soil test based nutrient recommendation + rice straw biochar) and lowest in T_1 (absolute control).

Table 4.31: Fractions of nitrogen at panicle initiation

Treatments	Total hydrolysable- N	Amino acid- N	Ammoniacal- N	Nitrate- N
	mg kg^{-1}			
T_1	821.96^{i}	768.14^{g}	39.20^{g}	17.65^{g}
T_2	1805.12^{f}	925.12^{de}	54.52^{b}	24.61^{d}
T_3	1868.65^{e}	918.24^{e}	54.10^{b}	24.46^{d}
T_4	1914.61^{d}	1164.82^{b}	51.18^{c}	28.01^{c}
T_5	2012.46^{c}	1248.51^{a}	54.81^{a}	30.08^{a}
T_6	2140.08^{b}	959.46^{d}	50.20^{d}	28.12^{b}
T_7	2168.06^{a}	1112.85^{c}	50.35^{d}	28.65^{b}
T_8	1321.64^{h}	825.11^{f}	45.46^{f}	20.35^{f}
T_9	1490.22^{g}	847.36^{f}	47.13^{e}	20.94^{e}
CD (0.05)	11.34	40.51	0.52	0.55

Ammoniacal-N at panicle initiation stage ranged from 39.20 to 54.81 mg kg^{-1} with significantly highest fraction in T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest in T_1 (absolute control).

Nitrate-N was significantly highest in T_5 (32.14 mg kg^{-1}) and lowest in T_1 (23.92 mg kg^{-1}) at panicle initiation stage of rice.

4.3.3.3. Phosphorus

4.3.3.3. 1. Phosphorus fractions before planting

Before planting, soluble-P was highest in T_5 (21.23 mg kg^{-1}) and it was statistically on par with T_3 (20.20 mg kg^{-1}). The lowest soluble-P content (16.00 mg kg^{-1}) was noted in T_1 (Table 4.32).

Table 4.32: Fractions of phosphorus before planting

Treatments	Soluble -P	Al-P	Fe-P	Sesquioxide occluded-P	Ca-P	Organic- P
	$mg\ kg^{-1}$					
T_1	16.00^{d}	14.61^{h}	133.92^{f}	45.84^{i}	30.00^{e}	320.60^{f}
T_2	19.86^{b}	16.84^{e}	136.00^{d}	48.00^{f}	35.78^{bc}	364.61^{c}
T_3	20.20^{ab}	17.00^{d}	136.86^{c}	48.12^{e}	35.42^{c}	364.82^{c}
T_4	18.41^{c}	17.08^{d}	137.01^{c}	48.85^{d}	31.40^{d}	365.12^{bc}
T_5	21.23^{a}	18.00^{a}	141.81^{a}	49.00^{c}	37.81^{a}	365.86^{b}
T_6	17.82^{c}	17.63^{b}	138.82^{b}	50.21^{a}	30.47^{de}	368.28^{a}
T_7	16.51^{d}	17.45^{c}	137.21^{c}	49.80^{b}	37.00^{ab}	368.90^{a}
T_8	16.11^{d}	16.07^{g}	135.00^{e}	46.10^{h}	30.26^{de}	325.62^{e}
T_9	16.26^{d}	16.20^{f}	135.54^{de}	46.23^{g}	30.12^{de}	326.83^{d}
CD (0.05)	1.05	0.12	0.73	0.09	1.35	0.82

The content of Al-P was highest in T_5 i.e., soil receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw (18.00 mg kg^{-1}) and it was followed by T_6 i.e., soil containing soil test based nutrient recommendation and rice husk biochar (17.63 mg kg^{-1}). Absolute control (T_1) recorded lowest (14.61 mg kg^{-1}) content of Al-P.

The fraction of Fe-P was highest in T_5 (141.81 mg kg^{-1}) and it was followed by T_6 (138.82 mg kg^{-1}). The lowest content of Fe-P was recorded in T_1 (133.92 mg kg^{-1}).

The value of sesquioxide occluded phosphorus ranged from 45.84 to 50.21 mg kg^{-1} with highest in T_6 and lowest in T_1. Statistically significant difference was noted in the sesquioxide occluded-P of treatments and they followed the order: $T_6 > T_7 > T_5 > T_4 > T_3 > T_2 > T_9 > T_8 > T_1$.

The content of Ca-P was statistically highest in T_5 (37.81 mg kg^{-1}) and T_7 (37.00 mg kg^{-1}). Whereas, lowest in T_1 (30.00 mg kg^{-1}).

Organic-P was statistically highest in soils applied with treatments T_7 (368.90 mgkg^{-1}) and T_6 (368.28 mg kg^{-1}) followed by treatments T_5 (365.86 mg kg^{-1}) and T_4 (365.12 mg kg^{-1}). The content was lowest (320.60 mg kg^{-1}) in absolute control (T_1).

4.3.3.3. 2. Phosphorus fractions at tillering

At tillering stage, soluble-P was statistically highest in T_5 (23.12 mg kg^{-1}) and T_3 (22.68 mg kg^{-1}). Soluble-P was lowest in T_1 (15.08 mg kg^{-1}) (Table 4.33).

The content of Al-P of treatments varied from 13.08 to 16.86 mg kg^{-1} with highest in T_5 and lowest in T_1.

The fraction of Fe-P at tillering stage was highest in T_5 (140.52 mg kg^{-1}) followed by T_6 (137.57 mg kg^{-1}) and lowest in T_1 (128.75 mg kg^{-1}).

Table 4.33: Fractions of phosphorus at tillering

Treatments	**Soluble -P**	**Al-P**	**Fe-P**	**Sesquioxide occluded-P**	**Ca-P**	**Organic- P**
	mg kg^{-1}					
T_1	15.08^{f}	13.08^{e}	128.75^{g}	45.00^{i}	29.24^{f}	318.64^{g}
T_2	21.95^{b}	14.01^{d}	135.82^{de}	47.00^{f}	36.75^{b}	363.00^{d}
T_3	22.68^{ab}	14.75^{c}	136.00^{cd}	47.56^{e}	36.56^{b}	363.17^{cd}
T_4	20.16^{c}	15.05^{c}	136.26^{cd}	48.13^{d}	32.00^{c}	364.08^{c}
T_5	23.12^{a}	16.86^{a}	140.52^{a}	48.50^{c}	38.27^{a}	365.20^{b}
T_6	19.56^{c}	16.00^{b}	137.57^{b}	49.64^{a}	31.68^{cd}	367.13^{a}
T_7	18.23^{d}	15.82^{b}	136.42^{c}	49.01^{b}	37.86^{a}	368.00^{a}
T_8	17.02^{e}	13.54^{de}	132.84^{f}	45.24^{h}	30.60^{e}	324.10^{f}
T_9	18.01^{de}	14.00^{d}	135.46^{e}	45.81^{g}	31.06^{de}	325.36^{e}
CD (0.05)	1.03	0.61	0.53	0.16	0.81	1.06

Sesquioxide occluded-P content of treatments differed significantly with highest in T_6 (49.64 mg kg^{-1}) and lowest in T_1 (45.00 mg kg^{-1}). Treatments obeyed the order: $T_6 > T_7 > T_5 > T_4 > T_3 > T_2 > T_9 > T_8 > T_1$.

Calcium bound phosphorus (Ca-P) was statistically highest in T_5 (38.27 mg kg^{-1}) and T_7 (37.86 mg kg^{-1}) and lowest in T_1 (29.24 mg kg^{-1}).

The fraction of organic-P was statistically highest in T_7 (368.00 mg kg^{-1}) and T_6 (367.13 mg kg^{-1}) followed by T_5 (365.20 mg kg^{-1}). Whereas, T_1 (318.64 mg kg^{-1}) recorded lowest organic-P fraction.

4.3.3.3. 3. Phosphorus fractions at panicle initiation

At panicle initiation stage, the content of soluble-P varied from 13.82 to 22.51 mg kg^{-1}. Soil receiving combined applications of soil test based nutrient recommendation and vermicomposted rice straw recorded (T_5) highest soluble-P and absolute control (T_1), the lowest (Table 4.34).

Aluminium bound phosphorus (Al-P) at panicle initiation stage ranged from 12.10 to 14.28 mg kg^{-1} with highest in T_5 and lowest in T_1.

The content of Fe-P in treatments varied from 124.08 to 138.86 mg kg^{-1} with highest being T_5 and lowest in T_1.

The fraction of sesquioxide occluded-P ranged from 42.16 to 49.21 mg kg^{-1}. Statistically highest content was noted in treatments T_6 (49.21 mg kg^{-1}) and T_7 (48.56 mg kg^{-1}) and lowest by T_1 (42.16 mg kg^{-1}).

The fraction of Ca-P ranged from 29.00 to 40.27 mg kg^{-1} with highest in T_5 followed by T_7 and lowest by T_1.

Table 4.34: Fractions of phosphorus at panicle initiation

Treatments	Soluble -P	Al-P	Fe-P	Sesquioxide occluded-P	Ca-P	Organic- P
	mg kg^{-1}					
T_1	13.82^{f}	12.10^{g}	124.08^{f}	42.16^{g}	29.00^{f}	314.87^{f}
T_2	21.07^{b}	12.72^{e}	134.23^{d}	46.00^{d}	37.21^{c}	360.01^{c}
T_3	21.40^{b}	12.86^{e}	134.52^{d}	47.01^{c}	37.00^{c}	360.26^{c}
T_4	19.28^{c}	13.01^{d}	135.56^{c}	47.84^{b}	32.48^{d}	361.24^{c}
T_5	22.51^{a}	14.28^{a}	138.86^{a}	48.01^{b}	40.27^{a}	362.86^{b}
T_6	18.65^{cd}	13.74^{b}	136.61^{b}	49.21^{a}	32.00^{de}	364.02^{b}
T_7	17.84^{de}	13.41^{c}	135.80^{bc}	48.56^{ab}	38.62^{b}	365.82^{a}
T_8	16.14^{e}	12.40^{f}	130.01^{e}	43.78^{f}	30.86^{e}	320.53^{e}
T_9	16.92^{e}	12.84^{e}	134.11^{d}	45.04^{e}	32.80^{d}	322.18^{d}
CD (0.05)	0.92	0.15	0.85	0.79	1.23	1.47

Soil containing combined application of soil test based nutrient recommendation and rice straw biochar (T_7) recorded highest (365.82 mg kg^{-1}) content of organically bound phosphorus and lowest (314.87 mg kg^{-1}) by absolute control (T_1).

4.3.3.4. Potassium

4.3.3.4.1. Potassium fractions before planting

Before planting, fractions of water soluble potassium in various treatments varied from 15.18 to 26.50 mg kg^{-1} (Table 4.35). Soil receiving combined application of soil test based nutrient recommendation and rice straw biochar (T_7) registered highest value and lowest by absolute control (T_1).

Table 4.35: Fractions of potassium before planting

Treatments	Water soluble-K	Exchangeable-K
	mg kg^{-1}	
T_1	15.18^{f}	108.26^{g}
T_2	18.53^{c}	123.01^{c}
T_3	18.64^{c}	122.83^{c}
T_4	16.28^{e}	114.15^{e}
T_5	22.81^{b}	134.67^{b}
T_6	17.65^{cd}	119.94^{d}
T_7	26.50^{a}	138.52^{a}
T_8	16.04^{ef}	112.08^{f}
T_9	17.38^{d}	115.00^{e}
CD (0.05)	1.09	1.15

Exchangeable potassium fraction was highest (138.52 mg kg^{-1}) in T_7 (soil test based nutrient recommendation + rice straw biochar) and it was followed by T_5 (soil test based nutrient recommendation + vermicomposted rice straw) having 134.67 mg kg^{-1} exchangeable-K. The lowest content was recorded in T_1 (absolute control) where, exchangeable-K was 108.26 mg kg^{-1}.

4.3.3.4.2. Potassium fractions at tillering

Water soluble-K content at tillering stage (Table 4.36) varied from 16.84 to 38.10 mg kg^{-1} with highest in soil containing combined application of soil test based nutrient recommendation and rice straw biochar (T_7) and lowest in absolute control (T_1). Treatment T_8 (soil test based nutrient recommendation + rice husk) and T_1 (absolute control) were statistically on par.

Table 4.36: Fractions of potassium at tillering

Treatments	**Water soluble-K**	**Exchangeable-K**
	mg kg^{-1}	
T_1	16.84^e	109.22^h
T_2	23.26^c	128.47^e
T_3	24.07^c	133.69^c
T_4	18.94^d	119.47^f
T_5	31.98^b	153.81^b
T_6	23.84^c	130.32^d
T_7	38.10^a	164.98^a
T_8	17.98^{de}	115.96^g
T_9	25.04^c	134.04^c
CD (0.05)	1.83	1.15

Statistically significant difference was observed in exchangeable potassium content of various treatments at tillering stage of rice. Exchangeable –K content varied from 109.22 to 164.98 mg kg^{-1} with highest in T_7 (soil test based nutrient recommendation + rice straw biochar) and lowest in absolute control (T_1). The different treatments compiled the order: $T_7 > T_5 > T_9 > T_3 > T_6 > T_2 > T_4 > T_8 > T_1$.

4.3.3.4.3. Potassium fractions at panicle initiation

At panicle initiation stage, water soluble potassium fraction of treatments varied from 18.06 to 47.21 mg kg^{-1} with highest in T_7 (soil test based nutrient recommendation + rice straw biochar) and lowest in absolute control (T_1). Water soluble-K content in various treatments followed the order: $T_7 > T_5 > T_9 > T_3 > T_6 > T_2 > T_4 > T_8 > T_1$ were in T_2 and T_6 are on par (Table 4.37).

Table 4.37: Fractions of potassium at panicle initiation

Treatments	**Water soluble-K**	**Exchangeable-K**
	mg kg^{-1}	
T_1	18.06^h	110.48^i
T_2	26.49^e	134.76^f
T_3	29.60^d	145.84^d
T_4	22.13^f	125.08^g
T_5	37.45^b	165.75^b
T_6	27.03^e	136.93^e
T_7	47.21^a	184.51^a
T_8	20.94^g	120.88^h
T_9	30.86^c	147.64^c
CD (0.05)	1.04	1.37

Exchangeable-K content of treatments ranged from 110.48 to 184.51 mg kg^{-1}. Statistically significant difference was observed among the treatments in their exchangeable-K content and they obeyed the order: $T_7 > T_5 > T_9 > T_3 > T_6 > T_2 > T_4 > T_8 > T_1$. Fraction was highest in soil receiving combined application of soil test based nutrient recommendation and rice straw biochar (T_7) and was lowest in absolute control (T_1).

4.3.3.5. Calcium

4.3.3.5.1. Calcium fractions before planting

Before planting (Table 4.38), water soluble calcium was highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest in T_1 (absolute control).

Exchangeable calcium varied from 190.95 to 214.68 mg kg^{-1} with lowest in absolute control (T_1) and highest in soil receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw (T_5).

Table 4.38: Fractions of calcium before planting

Treatments	Water soluble-Ca	Exchangeable-Ca
	mg kg^{-1}	
T_1	12.38^{d}	190.95^{d}
T_2	15.27^{c}	195.61^{c}
T_3	14.86^{c}	194.92^{c}
T_4	15.73^{c}	198.02^{c}
T_5	18.82^{a}	214.68^{a}
T_6	15.41^{c}	195.81^{c}
T_7	17.45^{b}	210.12^{b}
T_8	14.57^{c}	194.86^{c}
T_9	14.60^{c}	194.90^{c}
CD (0.05)	1.21	3.33

4.3.3.5.2. Calcium fractions at tillering

At tillering stage, water soluble calcium varied from 13.82 to 30.17 mg kg^{-1} and it was found to be highest in soil receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) and lowest in absolute control (T_1) (Table 4.39).

Exchangeable fraction of calcium differed significantly among the treatments and it was highest (264.61 mg kg^{-1}) in T_5 and lowest (172.16 mg kg^{-1}) in T_1.

Table 4.39: Fractions of calcium at tillering

Treatments	Water soluble-Ca	Exchangeable-Ca
	mg kg^{-1}	
T_1	13.82^{g}	172.16^{g}
T_2	20.87^{ef}	212.74^{e}
T_3	20.07^{f}	211.78^{e}
T_4	23.59^{c}	234.84^{c}
T_5	30.17^{a}	264.61^{a}
T_6	21.23^{e}	219.93^{d}
T_7	26.01^{b}	250.98^{b}
T_8	20.73^{ef}	207.65^{f}
T_9	22.46^{d}	220.71^{d}
CD (0.05)	0.82	2.11

4.3.3.5.3. Calcium fractions at panicle initiation

At panicle initiation stage, water soluble calcium (Table 4.40) was highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest in T_1 (absolute control).

Exchangeable calcium differed significantly among various treatments and it was highest in soil receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw (313.61 mg kg^{-1}) *i.e.*, T_5 and lowest in absolute control (150.01 mg kg^{-1}) *i.e.*, T_1.

Table 4.40: Fractions of calcium at panicle initiation

Treatments	**Water soluble-Ca**	**Exchangeable-Ca**
	mg kg^{-1}	
T_1	16.34^f	150.01^g
T_2	31.18^d	229.74^e
T_3	28.19^e	227.94^e
T_4	39.90^c	270.02^c
T_5	51.81^a	313.61^a
T_6	32.54^d	244.04^d
T_7	46.32^b	281.16^b
T_8	30.86^d	219.83^f
T_9	37.77^c	248.89^d
CD (0.05)	2.14	7.09

4.3.3.6. Magnesium

4.3.3.6.1. Magnesium fractions before planting

Before planting, water soluble magnesium in treatments varied from 5.60 to 7.46 mg kg^{-1} with highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest in T_1 (absolute control).

Exchangeable magnesium fraction of treatments ranged from 40.78 to 77.96 mg kg^{-1}. Soil receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw registered highest exchangeable magnesium (Table 4.41) whereas, it was lowest in absolute control.

Table 4.41: Fractions of magnesium before planting

Treatments	Water soluble-Mg	Exchangeable-Mg
	mg kg^{-1}	
T_1	5.60^{f}	40.78^{e}
T_2	6.88^{b}	67.20^{b}
T_3	6.86^{b}	66.80^{b}
T_4	6.52^{c}	65.86^{b}
T_5	7.46^{a}	77.96^{a}
T_6	6.46^{d}	60.90^{c}
T_7	6.84^{b}	66.60^{b}
T_8	5.61^{f}	50.86^{d}
T_9	5.82^{e}	50.90^{d}
CD (0.05)	0.057	2.41

4.3.3.6.2. Magnesium fractions at tillering

At tillering stage, water soluble magnesium differed statistically in various treatments and the content was highest (9.60 mg kg^{-1}) in T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest (6.40 mg kg^{-1}) in T_1 (absolute control).

Exchangeable magnesium fraction was highest (96.92 mg kg^{-1}) in soil receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) and it was followed by soil receiving combined application of soil test based nutrient recommendation and rice straw biochar (T_7) with 83.50 mg kg^{-1} exchangeable magnesium. Among the nine treatments, absolute control (T_1) recorded lowest (34.76 mgkg^{-1}) value.

Table 4.42: Fractions of magnesium at tillering

Treatments	Water soluble-Mg	Exchangeable-Mg
	mg kg^{-1}	
T_1	6.40^{h}	34.76^{h}
T_2	8.72^{bc}	75.70^{d}
T_3	8.76^{b}	75.23^{d}
T_4	8.62^{d}	80.27^{c}
T_5	9.60^{a}	96.92^{a}
T_6	8.56^{e}	70.96^{e}
T_7	8.68^{c}	83.50^{b}
T_8	7.41^{g}	54.27^{g}
T_9	7.82^{f}	58.36^{f}
CD (0.05)	0.059	2.37

4.3.3.6. 3. Magnesium fractions at panicle initiation

Water soluble magnesium in different treatments varied significantly (Table 4.43) and the content was highest (10.87 mg kg^{-1}) in T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest (7.10 mg kg^{-1}) in T_1 (absolute control).

Soil receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) registered highest (92.01 mg kg^{-1}) exchangeable magnesium fraction at panicle initiation stage. The lowest content (25.89 mg kg^{-1}) was recorded in absolute control (T_1).

Table 4.43: Fractions of magnesium at panicle initiation

Treatments	Water soluble-Mg	Exchangeable-Mg
	mg kg^{-1}	
T_1	7.10^{f}	25.89^{h}
T_2	9.74^{bc}	69.88^{d}
T_3	9.82^{b}	69.27^{d}
T_4	9.68^{bc}	74.25^{c}
T_5	10.87^{a}	92.01^{a}
T_6	9.62^{c}	64.18^{e}
T_7	9.78^{b}	77.78^{b}
T_8	8.61^{e}	46.41^{g}
T_9	9.02^{d}	52.44^{f}
CD (0.05)	0.16	1.96

4.3.3.7. Sulphur fractions

4.3.3.7.1. Sulphur fractions before planting

Before planting, no significant difference was observed in organic sulphur fraction (Table 4.44).

Available sulphur content differed significantly among the treatments and it varied from 4.07 to 4.52 mg kg^{-1}. Available-S content was significantly highest in T_3, T_4, T_5, T_6, and T_7. Absolute control recorded the lowest value.

Table 4.44: Fractions of sulphur before planting

Treatments	**Organic-S**	**Available-S**
	mg kg^{-1}	
T_1	656.20	4.07^{c}
T_2	657.18	4.20^{bc}
T_3	656.32	4.34^{ab}
T_4	657.41	4.50^{a}
T_5	657.38	4.52^{a}
T_6	656.44	4.48^{a}
T_7	656.30	4.36^{ab}
T_8	656.26	4.12^{bc}
T_9	656.28	4.14^{bc}
CD (0.05)	NS	0.26

4.3.3.7.2. Sulphur fractions at tillering

Organic sulphur fraction at tillering stage (Table 4.45) varied from 595.20 to 692.81 mg kg^{-1} with highest in soil receiving combined applications of soil test based nutrient recommendation and vermicomposted rice straw (T_5) and lowest in absolute control (T_1). Organic sulphur content in soil receiving combined applications of soil test based nutrient recommendation and vermicomposted rice husk application (T_4) was statistically on par with T_5. The different treatments in available sulphur content followed the order: $T_5 > T_4 > T_6 > T_7 > T_9 > T_8 > T_3 > T_2 > T_1$. Treatment T_7 was on par with T_6. Organic sulphur content in T_9 was on par with T_7. T_8 and T_3 are also statistically on par.

At tillering, available sulphur content of treatments varied from 3.96 to 7.16 mg kg^{-1} with highest in T_5 (soil test based nutrient recommendation+ vermicomposted rice straw) and lowest in T_1 (absolute control).

Table 4.45: Fractions of sulphur at tillering

Treatments	**Organic-S**	**Available-S**
	mg kg^{-1}	
T_1	595.20^{f}	3.96^{g}
T_2	662.12^{e}	4.38^{f}
T_3	683.30^{d}	6.30^{d}
T_4	691.86^{a}	6.68^{b}
T_5	692.81^{a}	7.16^{a}
T_6	686.82^{b}	6.52^{c}
T_7	686.48^{bc}	6.48^{c}
T_8	683.32^{d}	5.72^{e}
T_9	685.41^{c}	6.66^{b}
CD (0.05)	1.32	0.056

4.3.3.7.2. Sulphur fractions at panicle initiation stage

Organic sulphur fraction (Table 4.46) differed significantly at panicle initiation stage and it varied from 334.81 to 606.84 mg kg^{-1} with highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest in T_1 (absolute control). The organic sulphur content of various treatments is in the order: $T_5 > T_4 > T_6 > T_7 > T_9 > T_8 > T_3 > T_2 > T_1$. Whereas, the treatments T_7 and T_6, T_3, T_8, T_9 and T_7 are statistically on par in their organic sulphur content.

Available sulphur fraction at panicle initiation stage varied from 3.54 to 6.96 mg kg^{-1} with highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest in T_1 (absolute control). Available sulphur content in various treatment were followed the order: $T_5 > T_4 > T_9 > T_6 > T_3 > T_7 > T_8 > T_2 > T_1$. Treatments T_6 and T_3 and T_7 are statistically on par.

Table 4.46: Fractions of sulphur at panicle initiation

Treatments	Organic-S	Available-S
	mg kg^{-1}	
T_1	494.81^{f}	3.54^{g}
T_2	576.12^{e}	4.06^{f}
T_3	597.34^{d}	6.14^{d}
T_4	605.31^{b}	6.52^{b}
T_5	606.84^{a}	6.96^{a}
T_6	598.82^{c}	6.34^{c}
T_7	598.48^{cd}	6.13^{d}
T_8	597.42^{d}	5.48^{e}
T_9	597.63^{d}	6.36^{c}
CD (0.05)	1.17	0.028

4.3.3.8. Silicon fractions

4.3.3.8.1. Silicon fractions before planting

Before planting (Table 4.47) mobile silicon was found to be highest in T_6 (26.64 mg kg^{-1}) receiving soil test based nutrient recommendation and rice husk biochar application. However, T_7 (23.85 mg kg^{-1}) receiving combined applications of soil test based nutrient recommendation and rice straw biochar application was statistically on par with T_6. The lowest mobile silicon content of 20.12 mg kg^{-1} was recorded in T_1 (absolute control) and T_8 (soil test based nutrient recommendation+ rice husk). The mobile silicon content in T_9 (soil test based nutrient recommendation + rice straw) was statistically on par with T_8 and T_1. However, T_9 also on par with T_2 (Adhoc organic KAU POP) and T_3 (soil test based nutrient recommendation + FYM) containing 21.33 mg kg^{-1} of mobile silicon.

Table 4.47: Fractions of silicon before planting

Treatments	Mobile-Si	Adsorbed- Si	Organic- Si	Occluded- Si	Amorphous- Si	Residual- Si
	mgkg^{-1}					
T_1	20.12^{e}	16.5^{c}	451.8^{d}	392.10^{g}	62610	34466.1^{i}
T_2	21.33^{d}	16.6^{c}	451.8^{d}	396.06^{f}	62616	36172.1^{h}
T_3	21.33^{d}	16.6^{c}	451.8^{d}	396.06^{f}	62616	36505.4^{g}
T_4	22.64^{c}	17.0^{b}	454.6^{c}	406.08^{d}	62616	48818.1^{d}
T_5	23.85^{b}	17.2^{ab}	454.6^{c}	408.26^{c}	62616	49498.6^{c}
T_6	26.64^{a}	17.4^{a}	476.1^{a}	412.20^{a}	62616	54796.4^{a}
T_7	25.68^{a}	17.4^{a}	460.2^{b}	410.10^{b}	62616	52707.6^{b}
T_8	20.12^{e}	16.6^{c}	452.3^{d}	401.10^{e}	62616	41874.4^{f}
T_9	20.86^{de}	16.7^{c}	452.3^{d}	401.10^{e}	62616	42953.5^{e}
CD (0.05)	1.12	0.25	1.17	1.65	NS	115.06

The mobile silicon content of treatments receiving rice residues and their products obeyed the order: $T_6 > T_7 > T_5 > T_4 > T_8 > T_9$. Persual data in Table 4.47 shows that, no significant difference was observed among biochar containing treatments (T_6 and T_7) and also in residue carrying treatments (T_8 and T_9) before planting.

The adsorbed silicon content before planting varied from 16.5 to 17.4 mg kg^{-1}. The treatments T_7 and T_6 (17.4 mg kg^{-1}) recorded highest silicon content. However, T_5 was statistically on par with T_7 and T_6. Adsorbed silicon in T_1 was on par with T_8, T_2, T_3, and T_9.

Before planting, organic silicon content of various treatments varied from 451.8 to 476.1 mg kg^{-1}. The treatments obeyed the order: $T_6 > T_7 > T_4 = T_5 > T_9 = T_8 > T_2 = T_3 = T_1$. The organic silicon content was highest in T_6 (476.1 mg kg^{-1}) containing soil test based nutrient recommendation +rice husk biochar.

Before planting, occluded silicon fraction varied from 392.1 to 412.2 mg kg^{-1}. Treatment T_6 receiving combined applications of soil test based nutrient recommendation and rice husk biochar recorded highest content and lowest by T_1 (absolute control). Occluded silicon content in various treatments followed the order: $T_6 > T_7 > T_5 > T_4 > T_9 = T_8 > T_3 = T_2 > T_1$.

Statistically no significant difference was observed in the case of amorphous silicon fraction before planting of rice.

Residual silicon fraction before planting varied from 34466.15 to 54796.42 mg kg^{-1}. Treatment T_6 (soil test based nutrient recommendation+ rice husk biochar) recorded highest residual silicon content and lowest by T_1 (absolute control). Treatments differed significantly and the residual silicon fraction in various treatments followed the order: $T_6 > T_7 > T_5 > T_4 > T_9 > T_8 > T_3 > T_2 > T_1$.

4.3.3.8.2. Silicon fractions at tillering

At tillering, mobile silicon was found to be highest in T_6 (28.79 mg kg^{-1}) and lowest in T_1 (21.21 mg kg^{-1}). The effect of treatments on mobile silicon fraction in soil catched the order: $T_6 > T_7 > T_5 > T_4 > T_9 > T_2 = T_3 = T_8 > T_1$ (Table 4.48).

Adsorbed silicon content at tillering stage varied from 16.0 to 17.0 mg kg^{-1}. Treatments T_7 and T_6 recorded highest adsorbed silicon. Treatments T_5 and T_4 are statistically on par with T_7 and T_6. The lowest content was recorded by treatment T_1 and is on par with T_2, T_3, and T_8. The treatments followed the order: $T_7 = T_6 > T_5 > T_4 > T_9 > T_8 > T_3 > T_2 > T_1$.

At tillering, organic silicon varied from 440.2 to 470.0 mg kg^{-1} with highest in T_6 and lowest in T_1. Organic silicon fraction in various treatments catched the order: $T_6 > T_7 > T_5 > T_4 = T_8 = T_9 > T_3 > T_2 > T_1$.

Occluded silicon fraction at tillering was varied from 384.36 to 407.7 mg kg^{-1} with highest in T_6 (soil test based nutrient recommendation + rice husk biochar) and lowest in T_1 (absolute control). Occluded silicon in various treatments followed the order: $T_6 > T_7 > T_5 > T_4 > T_9 > T_8 > T_3 > T_2 > T_1$.

Amorphous silicon fraction does not differed significantly among the various treatments studied at tillering stage of rice.

Residual silicon fraction shows significant variation in different treatments and the content varied from 32262.43 to 54274.41 mg kg^{-1}. Treatment T_6 (soil test based nutrient recommendation + rice husk biochar) recorded statistically highest residual silicon and lowest by T_1 (absolute control. Residual silicon content in various treatments followed the order: $T_6 > T_7 > T_5 > T_4 > T_9 > T_8 > T_2 > T_3 > T_1$. However, T_3 was statistically on par with T_2.

Table 4.48: Fractions of silicon at tillering

Treatments	Mobile-Si	Adsorbed- Si	Organic- Si	Occluded- Si	Amorphous- Si	Residual- Si
	mgkg^{-1}					
T_1	21.21^{g}	16.0^{d}	440.2^{f}	386.2^{g}	62514	32262.4^{h}
T_2	22.43^{f}	16.0^{d}	446.1^{e}	390.2^{f}	62616	35715.3^{g}
T_3	22.43^{f}	16.1^{d}	448.2^{d}	390.2^{f}	62618	35683.2^{g}
T_4	23.94^{d}	16.7^{ab}	450.1^{c}	400.9^{d}	62521	48221.2^{d}
T_5	25.30^{c}	16.8^{a}	451.1^{c}	403.4^{c}	62624	48900.5^{c}
T_6	28.79^{a}	17.0^{a}	470.0^{a}	407.7^{a}	62622	54274.4^{a}
T_7	27.82^{b}	17.0^{a}	456.3^{b}	405.4^{b}	62622	52480.0^{b}
T_8	22.43^{f}	16.2^{cd}	450.1^{c}	395.3^{e}	62616	40964.0^{f}
T_9	22.88^{e}	16.4^{bc}	450.1^{c}	395.4^{e}	62617	42080.1^{e}
CD (0.05)	0.09	0.30	1.58	1.83	NS	122.13

4.3.3.8.3. Silicon fractions at panicle initiation

At panicle initiation stage (Table 4.49), the content of mobile silicon was varied from 22.12 to 30.84 mg kg^{-1}, with lowest in T_1 and highest in T_6. Treatment T_7 (30.84 mg kg^{-1}) was on par with T_6. Mobile silicon in various treatments obeyed the order: $T_6 > T_7 > T_5 > T_4 > T_9 > T_8 > T_3 > T_2 > T_1$.

At panicle initiation adsorbed silicon in various treatments varied from 15.6 to 16.8 mg kg^{-1}. The highest content was observed in treatment T_7 and T_6. The lowest content was observed in T_1. However, T_1 was statistically on par with T_2 and T_3. Adsorbed silicon at panicle initiation followed the order: $T_7 = T_6 > T_5 > T_4 > T_9 > T_8 > T_3 > T_2 > T_1$.

Organic silicon fraction at panicle initiation stage varied from 436.4 to 468.4 mg kg^{-1}. Treatment receiving combined applications of soil test based nutrient recommendation and rice husk biochar (T_6) recorded highest value and lowest by absolute control (T_1). The treatments followed the order: $T_6 > T_7 > T_4 = T_5 > T_9 > T_8 > T_3 > T_2 > T_1$.

At panicle initiation stage, occluded silicon varied from 370.1 to 397.49 mg kg^{-1}. Treatment T_6 (soil test based nutrient recommendation + rice husk biochar) recorded highest value and lowest by T_1 (absolute control). Occluded silicon fraction in various treatments obeyed the order: $T_6 > T_7 > T_5 > T_4 > T_9 > T_8 > T_3 > T_2 > T_1$.

Statistically no significant difference is observed in the content of amorphous silicon fraction in various treatments at panicle initiation stage.

At panicle initiation stage, residual silicon varied from 28697.11 to 53248.41 mg kg^{-1}. The highest residual fraction was observed in T_6 (soil test based nutrient recommendation+ rice husk biochar). However, T_7 (soil test based nutrient recommendation+ rice straw biochar) was on par with T_6. Residual silicon fraction was lowest in T_1 (28697.11 mg kg^{-1}). Residual silicon fraction of treatments at panicle initiation followed the order: $T_6 > T_7 > T_5 > T_4 > T_9 > T_8 > T_3 > T_2 > T_1$. Residual silicon content in T_2 was statistically on par with T_3.

Table 4.49: Fractions of silicon at panicle initiation

Treatments	Mobile-Si	Adsorbed- Si	Organic- Si	Occluded- Si	Amorphous- Si	Residual- Si
	mgkg^{-1}					
T_1	22.12^{f}	15.6^{e}	436.4^{f}	370.1^{g}	62612	28697.1^{g}
T_2	23.52^{e}	15.7^{de}	438.1^{e}	374.4^{f}	62614	34074.6^{f}
T_3	23.52^{e}	15.7^{de}	446.2^{d}	374.4^{f}	62614	34135.7^{f}
T_4	26.74^{c}	16.5^{b}	448.2^{c}	386.6^{d}	62517	46896.5^{c}
T_5	28.26^{b}	16.6^{b}	448.2^{c}	389.5^{c}	62620	47707.2^{b}
T_6	31.10^{a}	16.8^{a}	468.4^{a}	397.5^{a}	62618	53248.4^{a}
T_7	30.84^{a}	16.8^{a}	450.0^{b}	392.7^{b}	62618	53133.5^{a}
T_8	24.01^{e}	15.8^{d}	446.7^{cd}	379.5^{e}	62614	39148.6^{e}
T_9	25.82^{d}	16.0^{c}	447.8^{c}	380.5^{e}	62615	40336.5^{d}
CD (0.05)	0.54	0.21	1.52	1.69	NS	174.16

4.3.4. Enzyme activity

The activity of enzymes *viz.*, dehydrogenase, urease and acid phosphatase were analysed at four stages (before planting, at tillering, panicle initiation, and at harvest) during the field experiment.

4.3.4.1. Dehydrogenase activity

Data on dehydrogenase activity at different growth stages of rice after treatment application are shown in Table 4.50.

Dehydrogenase activity of all the treatments was found to increased upto panicle initiation stage followed by a decrease at harvest.

Table 4.50: Effect of treatments on dehydrogenase activity

Treatments	**Dehydrogenase activity (µg TPF $g^{-1}day^{-1}$)**			
	Before planting	**At tillering**	**Panicle initiation**	**Harvest**
T_1	38.57^e	47.43^g	52.36^g	36.42^f
T_2	55.44^b	73.57^c	82.64^c	61.48^c
T_3	57.92^a	76.78^b	86.21^b	64.21^b
T_4	55.18^b	71.30^d	79.36^d	60.55^c
T_5	59.66^a	79.78^a	90.84^a	66.36^a
T_6	47.75^c	60.67^e	67.13^e	52.05^d
T_7	48.02^c	60.94^e	67.40^e	52.33^d
T_8	40.83^d	53.55^f	59.91^f	45.07^e
T_9	47.28^c	60.00^e	66.36^e	51.54^d
CD (0.05)	1.91	2.21	1.51	2.08

Just before planting, dehydrogenase activity varied from 38.57 to 59.66µgTPF$g^{-1}day^{-1}$ with lowest in T_1 and highest in T_5. However, T_3 (57.92 µg TPF $g^{-1}day^{-1}$) was on par with T_5. The dehydrogenase activity at tillering was in the order: $T_5 > T_3 > T_2 > T_4 > T_7 > T_6 > T_9 > T_8 > T_1$.

At tillering, dehydrogenase activity was found to be highest in T_5 receiving vermicomposted rice straw and soil test based nutrient recommendation (79.78 µg TPFg^{-1}

day^{-1}). The lowest dehydrogenase activity of 47.43 µg TPF g^{-1} day^{-1} was observed in T_1 (absolute control). The dehydrogenase activity at tillering followed the order: $T_5 > T_3 > T_2 > T_4 > T_7 > T_6 > T_9 > T_8 > T_1$.

At panicle initiation stage, T_5 (90.84 µg TPF g^{-1} day^{-1}) recorded highest dehydrogenase activity and T_1 (52.36 µg TPF g^{-1} day^{-1}) the lowest. The dehydrogenase activity of various treatments followed the order: $T_5 > T_3 > T_2 > T_4 > T_7 > T_9 > T_6 > T_8 > T_1$.

The dehydrogenase activity of various treatments at harvest follows the order: $T_5 > T_3 > T_2 > T_4 > T_7 > T_6 > T_9 > T_8 > T_1$. Dehydrogenase activity varied from 36.42 to 66.36 µg TPF g^{-1} day^{-1} with highest in T_5 receiving vermicomposted rice straw and soil test based nutrient recommendation and lowest dehydrogenase activity was recorded in T_1 (36.42 µg TPF g^{-1} day^{-1}).

While considering the different growth stages of rice, dehydrogenase activity was found to increase upto panicle initiation followed by a decrease at harvest.

4.3.4.2. Urease activity

Urease activity at different stages of crop growth after the application of treatments are given in Table 4.51. Data showed that urease activity of all treatments increased upto panicle initiation stage and thereafter decreased at harvest. The urease activity of T_1 at harvest (29.57 µg N-NH$_4$ g^{-1} hr^{-1}) was comparatively lower than enzyme activity just before planting (32.54 µg N-NH$_4$ g^{-1} hr^{-1}). Whereas, in other treatments urease activity at harvest was found to be higher than the activity before planting.

Urease activity was found to be highest in T_5 and lowest in T_1. Similar trend was seen at all stages of crop. However, urease activity in T_3 was statistically on par with T_5 at tillering stage of rice. The effect of treatments differed significantly at all the four growth stages.

Urease activity varied from 32.54 to 81.63 µg N-NH$_4$ g^{-1} hr^{-1}, 37.47 to 100.69 µg N-NH$_4$ g^{-1} hr^{-1}, 44.93 to 110.68 µg N-NH$_4$ g^{-1} hr^{-1}, and 29.57 to 89.59 µg N-NH$_4$ g^{-1} hr^{-1} at just before planting, tillering, panicle initiation and at harvest.

Table 4.51: Effect of treatments on urease activity

Treatments	Urease activity (µg N-NH_4 g^{-1} hr^{-1})			
	Before planting	**At tillering**	**Panicle initiation**	**Harvest**
T_1	32.54^h	37.47^f	44.93^g	29.57^f
T_2	60.86^d	89.93^b	99.48^c	72.01^b
T_3	77.53^b	96.96^a	106.67^b	74.01^b
T_4	70.36^c	88.29^b	97.32^c	71.94^b
T_5	81.63^a	100.69^a	110.68^a	89.59^a
T_6	48.28^{ef}	64.75^{cd}	72.98^{de}	53.77^{cd}
T_7	50.84^e	67.32^c	75.67^d	56.33^c
T_8	40.83^g	56.90^e	64.96^f	46.17^e
T_9	46.25^f	62.61^d	70.79^e	48.96^{de}
CD (0.05)	3.78	4.30	3.57	5.43

The effect of treatments differed significantly at all the four intervals. The effect of treatments on urease activity followed the same order on all stages even though some statistical similarity observed among the treatments. Urease activity at all the stages was in the order: $T_5 > T_3 > T_2 > T_4 > T_7 > T_6 > T_9 > T_8 > T_1$.

4.3.4.3. Acid phosphatase activity

The effect of various treatments on acid phosphatase activity are given in Table 4.52. Before planting, at tillering, panicle initiation, and at harvest, acid phosphatase activity varied from 37.62 to 86.85 µg PNP g^{-1} hr^{-1}, 42.86 to 105.25 µg PNP $g^{-1}hr^{-1}$, 45.48 to 113.88 µg PNP g^{-1} hr^{-1}, and 34.18 to 91.35 µg PNP g^{-1} hr^{-1}respectively. The highest acid phosphatase activity was recorded by T_5 and lowest by T_1 at all stages.

Highest acid phosphatase activity was observed at panicle initiation stage and lowest before planting in all treatments except T_1. In treatment T_1, acid phosphatase activity was numerically lowest at harvest with a value of 34.18 µg PNP g^{-1} hr^{-1}.

Table 4.52: Effect of treatments on acid phosphatase activity

Treatments	Acid phosphatase activity (µg PNP $g^{-1}hr^{-1}$)			
	Before planting	**At tillering**	**Panicle initiation**	**Harvest**
T_1	37.62^f	42.86^g	45.48^g	34.18^g
T_2	68.31^c	85.38^c	93.91^c	72.50^c
T_3	80.62^b	98.05^b	106.76^b	84.98^b
T_4	79.37^b	95.43^b	103.42^b	83.38^b
T_5	86.85^a	105.25^a	113.88^a	91.35^a
T_6	58.24^d	72.70^d	79.93^d	61.85^d
T_7	58.27^d	72.75^d	79.99^d	61.87^d
T_8	48.17^e	60.25^f	66.28^f	51.18^f
T_9	55.16^d	68.52^e	75.20^e	58.50^e
CD (0.05)	4.54	3.50	3.58	2.26

At all stages, the acid phosphatase activity of treatment followed the same sequence: $T_5 > T_3 > T_4 > T_2 > T_7 > T_6 > T_9 > T_8 > T_1$. However T_3 and T_4, T_6 and T_7 were statistically on par in their acid phosphatase activity.

4.3.5. Plant analysis

Plant analysis was carried out at different stages of rice *viz*., tillering, panicle initiation, and at harvest.

4.3.5.1. Nitrogen

The effects of treatments on nitrogen content in rice at different stages are presented in Table 4.53.

The data presented in Table 4.53 revealed that, the nitrogen content in rice at tillering differed significantly by the application of treatments and it obeyed the order: $T_5 > T_2 > T_6 > T_3 > T_4 > T_7 > T_9 > T_8 > T_1$. The application of treatment T_5 recorded highest nitrogen content (2.43 %). However, nitrogen content in T_2 (2.37 %) was statistically on par with T_5. The lowest nitrogen content was recorded by the treatment T_1 (absolute control) with 2.00 per cent nitrogen.

Table 4.53: Effect of treatments on nitrogen content (%) in plant

Treatments	Nitrogen content (%)		
	At tillering	Panicle initiation	Harvest
T_1	2.00^{e}	0.79^{g}	0.38^{e}
T_2	2.37^{ab}	2.55^{b}	0.52^{b}
T_3	2.31^{bc}	2.09^{c}	0.50^{b}
T_4	2.31^{bc}	2.11^{c}	0.51^{b}
T_5	2.43^{a}	2.88^{a}	0.56^{a}
T_6	2.31^{bc}	1.98^{de}	0.45^{c}
T_7	2.31^{bc}	2.06^{cd}	0.46^{c}
T_8	2.15^{d}	1.88^{f}	0.40^{de}
T_9	2.29^{c}	1.93^{ef}	0.43^{cd}
CD (0.05)	0.07	0.09	0.04

At panicle initiation stage, rice grown under T_5 receiving vermicomposted rice straw and soil test based nutrient recommendation showed highest nitrogen content (2.88%) whereas lowest nitrogen content was observed in T_1 (0.79%). The effect of various treatments on nitrogen content in rice at panicle initiation followed the order: $T_5 > T_2 > T_4 > T_3 > T_7 > T_6 > T_9 > T_8 > T_1$.

The effect of treatments on plant nitrogen at harvest followed the same sequence as that in panicle initiation stage but the nitrogen content was found to get decreased on comparison with panicle initiation stage. The effect of treatments on nitrogen content at harvest was in the order: $T_5 > T_2 > T_4 > T_3 > T_7 > T_6 > T_9 > T_8 > T_1$. The highest plant nitrogen at harvest was recorded by treatment T_5 (0.56 %) and lowest by T_1 (0.38 %). However, T_8 (0.40 %) was statistically on par with T_1.

4.3.5.2. Phosphorus

The data on phosphorus content in plant at tillering, panicle initiation and harvest are given in Table 4.54.

Rice grown under treatment T_5 receiving combined application of vermicomposted rice straw and soil test based nutrient recommendation showed highest phosphorus content

(0.38 %) at tillering stage. However, T_4, T_2, and T_3 with 0.36 per cent phosphorus was statistically on par with T_5. As expected rice grown under T_1 (absolute control) recorded lowest plant phosphorus (0.23 %).

At panicle initiation stage, statistically highest plant phosphorus content was recorded by T_5 (0.31%) receiving vermicomposted rice straw and soil test based nutrient recommendation. The lowest phosphorus content of 0.14 per cent was noted in rice grown under T_1 (absolute control). Phosphorus content in rice grown under T_4, T_2, and T_3 were similar with 0.28 per cent at panicle initiation stage. Similarly, application of T_6 and T_7 recorded same phosphorus content (0.25 %) in plant. However, phosphorus content in T_8 and T_9 (0.24 %) were statistically on par with T_6 and T_7.

Table 4.54: Effect of treatments on phosphorus content (%) in plant

Treatments	**Phosphorus content (%)**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	0.23^{d}	0.14^{d}	0.12^{d}
T_2	0.36^{a}	0.28^{b}	0.18^{b}
T_3	0.36^{a}	0.28^{b}	0.18^{b}
T_4	0.36^{a}	0.28^{b}	0.18^{b}
T_5	0.38^{a}	0.31^{a}	0.20^{a}
T_6	0.31^{b}	0.25^{c}	0.16^{c}
T_7	0.31^{b}	0.25^{c}	0.16^{c}
T_8	0.28^{c}	0.24^{c}	0.15^{c}
T_9	0.30^{bc}	0.24^{c}	0.16^{c}
CD (0.05)	0.03	0.02	0.02

At harvest, phosphorus content in plant grown under T_5 (0.20 %) was the highest. The lowest plant phosphorus content of 0.12 per cent was noted in T_1 (absolute control).

4.3.5.3. Potassium

The effect treatments on potassium content in rice at different growth stages are given in Table 4.55.

The highest plant potassium content at tillering stage was observed in T_7 (2.08 %) receiving combined applications of rice biochar and soil test based nutrient recommendation. As expected, potassium content in rice grown under T_1 (absolute control) was lowest (1.16 %) compared to all other treatments. The effect of treatments on potassium content in rice followed the order: $T_7 > T_5 > T_3 > T_2 > T_6 > T_4 > T_9 > T_8 > T_1$. Potassium content of rice in T_2 (1.96 %), T_3 (1.97 %), and T_5 (1.99 %) are statistically were on par. Similarly, potassium content in T_8 (1.74 %) and T_9 (1.75 %) were also statistically on par.

Table 4.55: Effect of treatments on potassium content (%) in plant

Treatments	**Potassium content (%)**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	1.16^f	1.08^f	0.47^g
T_2	1.96^b	2.23^c	1.04^c
T_3	1.97^b	2.24^c	1.04^c
T_4	1.81^d	2.10^d	0.72^e
T_5	1.99^b	2.46^{ab}	1.11^b
T_6	1.91^c	2.18^{cd}	0.86^d
T_7	2.08^a	2.50^a	1.15^a
T_8	1.74^e	1.52^e	0.53^f
T_9	1.75^e	2.38^b	1.04^c
CD (0.05)	0.04	0.11	0.04

At panicle initiation stage, highest potassium content in plant was observed in T_7 (2.50 %). However, potassium content in plant grown under treatment T_5 (2.46 %) receiving combined applications of vermicomposted rice straw and soil test based nutrient recommendation was statistically on par with T_7 receiving combined applications of rice straw biochar and soil test based nutrient recommendation. The lowest potassium content was observed in rice grown under T_1 (1.08 %): absolute control.

At harvest potassium content of plant was highest in T_7 (1.15 %) and lowest in T_1 (0.47 %). The effect of treatment on plant potassium at harvest followed the order: $T_7 > T_5 > T_2 = T_9 = T_3 > T_6 > T_4 > T_8 > T_1$.

4.3.5.4. Calcium

The effect of treatments on calcium content in rice at various growth stages are presented in Table 4.56.

At tillering, highest calcium content was observed in rice grown under T_5 (937.80 mg kg^{-1}) receiving combined applications of vermicomposted rice straw and soil test based nutrient recommendation and lowest in T_1 (846.12 mg kg^{-1}): absolute control.

Statistically significant variation was observed in calcium content of rice at panicle initiation stage. The effect of treatments on calcium content of rice obeyed the order: $T_5 > T_7 > T_4 > T_9 > T_6 > T_2 > T_3 > T_8 > T_1$. Calcium content in T_9 and T_6 are statistically on par. The highest plant calcium content was observed in T_5 (958.32 mg kg^{-1}) receiving combined applications of vermicomposted rice straw and soil test based nutrient recommendation and lowest in T_1 (850.02 mg kg^{-1}): absolute control.

Table 4.56: Effect of treatments on calcium content (mg kg^{-1}) in rice

Treatments	**Calcium content (mg kg^{-1})**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	846.12^{f}	850.02^{h}	823.20^{g}
T_2	905.30^{cd}	910.85^{e}	896.31^{e}
T_3	904.50^{d}	908.38^{f}	894.65^{e}
T_4	916.80^{b}	930.81^{c}	908.35^{cd}
T_5	937.80^{a}	958.32^{a}	938.22^{a}
T_6	910.60^{c}	925.33^{d}	906.43^{d}
T_7	918.00^{b}	940.06^{b}	918.14^{b}
T_8	890.30^{e}	898.32^{g}	875.37^{f}
T_9	890.67^{e}	926.32^{d}	910.52^{c}
CD (0.05)	6.06	2.11	3.55

At harvest stage, the effect of treatments on calcium content of plant was in the order: $T_5 > T_7 > T_9 > T_4 > T_6 > T_2 > T_3 > T_8 > T_1$. The calcium content of rice grown under treatments T_9 and T_4, T_6 and T_4, T_2 and T_3 are statistically on par. The highest calcium content was observed in rice grown under T_5 (938.22 mg kg^{-1}) receiving combined applications of vermicomposted rice straw and soil test based nutrient recommendation and lowest content of calcium in T_1 (823.20 mg kg^{-1}): absolute control.

4.3.5.5. Magnesium

The effect of treatments on magnesium content in rice at tillering, panicle initiation, and harvest are given in Table 4.57.

At tillering stage, magnesium content of rice was varied from 218.03 to 329.44 mg kg^{-1} with highest in T_5 (329.44 mg kg^{-1}) receiving combined applications of vermicomposted rice straw and soil test based nutrient recommendation and lowest (218.03 mg kg^{-1}) in absolute control (T_1). The effect of various treatments on magnesium content followed the order: $T_5 > T_2 > T_3 > T_7 > T_4 > T_6 > T_9 > T_8 > T_1$. The magnesium content in T_3 and T_7 are statistically on par.

Table 4.57: Effect of treatments on magnesium content (mg kg^{-1}) in rice

Treatments	**Magnesium content (mg kg^{-1})**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	218.03^{h}	186.12^{f}	168.84^{h}
T_2	322.12^{b}	317.14^{a}	302.71^{a}
T_3	317.25^{c}	305.75^{b}	280.80^{b}
T_4	310.12^{d}	256.86^{c}	236.11^{e}
T_5	329.44^{a}	318.75^{a}	307.96^{a}
T_6	282.27^{e}	235.26^{d}	218.34^{f}
T_7	315.69^{c}	304.48^{b}	274.78^{c}
T_8	263.47^{g}	216.14^{e}	192.12^{g}
T_9	266.32^{f}	260.18^{c}	248.37^{d}
CD (0.05)	1.91	3.42	6.01

At panicle initiation stage, highest magnesium content was observed in rice grown under T_5 (318.75 mg kg^{-1}): soil test based nutrient recommendation+ vermicomposted rice straw, and lowest in T_1 (186.12 mg kg^{-1}): absolute control. However, treatments T_2 (317.14 mg kg^{-1}): Adhoc KAU organic POP was statistically on par with T_5. The magnesium content in T_3 (305.75 mg kg^{-1}): soil test based nutrient recommendation + FYM was on par with T_7 (304.48 mg kg^{-1}): soil test based nutrient recommendation + rice straw biochar. Similarly, magnesium content in rice grown under T_9 (260.18 mg kg^{-1}): soil test based nutrient recommendation + rice straw was statistically on par with T_4 (256.86 mg kg^{-1}): soil test based nutrient recommendation + vermicomposted rice husk at panicle initiation stage.

At harvest, highest magnesium content in plant was recorded by T_5 (307.96 mg kg^{-1}) receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw and lowest (168.84 mg kg^{-1}) in T_1 (absolute control). However, the magnesium content of T_2 (302.71 mg kg^{-1}) receiving Adhoc recommendation of organic KAU POP was statistically on par with T_5 at harvest.

4.3.5.6. Sulphur

The effect of treatments on plant sulphur at different growth stages are presented in Table 4.58.

At tillering, sulphur content in plant varied from 710.70 to 830.10 mg $kg^{-1}$with lowest in T_1 (absolute control) and highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw). The effect of treatments on plant sulphur content followed the order: $T_5 > T_4 > T_6 > T_7 > T_3 > T_9 > T_8 > T_2 > T_1$. The sulphur content in T_7 (810.20 mg kg^{-1}) was on par with T_6 (811.30 mg kg^{-1}).

Table 4.58: Effect of treatments on sulphur content (mg kg^{-1}) in rice

Treatments	**Sulphur content (mg kg^{-1})**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	710.70^h	678.30^i	608.90^i
T_2	729.10^g	708.00^h	684.50^g
T_3	792.50^d	786.21^e	693.60^f
T_4	824.30^b	820.00^b	733.20^b
T_5	830.10^a	826.84^a	743.30^a
T_6	811.30^c	808.10^c	722.80^c
T_7	810.20^c	803.30^d	707.90^d
T_8	760.00^f	727.42^g	618.70^h
T_9	765.50^e	743.18^f	703.00^e
CD (0.05)	2.98	2.17	3.78

At panicle initiation stage, significant variation was observed among various treatments on plant sulphur content. The effect of treatments on plant sulphur content at panicle initiation was in the order: $T_5 > T_4 > T_6 > T_7 > T_3 > T_9 > T_8 > T_2 > T_1$. The highest sulphur content was observed in T_5 (826.84 mg kg^{-1}): soil test based nutrient recommendation + vermicomposted rice straw, and lowest in T_1 (678.30 mg kg^{-1}): absolute control.

At harvest, the effect of treatments on plant sulphur content follows the order: $T_5 > T_4 > T_6 > T_7 > T_9 > T_3 > T_2 > T_8 > T_1$. The highest plant sulphur content of 743.30 mg kg^{-1}was recorded by T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest content of 608.90 mg kg^{-1} sulphur by T_1 (absolute control).

4.3.5.7. Iron

The effect of treatments on iron content in plant at different growth stage is given in Table 4.59.

At tillering, iron content in rice varied from 763.83 to 1004.00 mg kg^{-1} with lowest in T_1 (absolute control) and highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw). The effect of treatments on iron content was in the order: $T_5 > T_7 > T_2 > T_3 > T_4 > T_6 > T_9 > T_8 > T_1$. The iron content in T_3 was on par with T_2. Similarly, T_4 was on par with T_3.

Table 4.59: Effect of treatments on iron content (mg kg^{-1}) in rice

Treatments	**Iron content (mg kg^{-1})**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	763.82^{h}	686.24^{h}	548.96^{h}
T_2	930.00^{c}	861.76^{b}	707.30^{c}
T_3	926.51^{cd}	838.42^{c}	694.86^{d}
T_4	923.14^{d}	824.16^{d}	634.10^{e}
T_5	1004.00^{a}	883.21^{a}	776.00^{a}
T_6	892.04^{e}	718.70^{f}	603.00^{f}
T_7	969.75^{b}	862.87^{b}	731.00^{b}
T_8	808.73^{g}	702.31^{g}	568.64^{g}
T_9	823.12^{f}	736.80^{e}	708.00^{c}
CD (0.05)	5.47	7.28	3.17

At panicle initiation stage, the effect of treatments on plant iron content obeyed the order: $T_5 > T_7 > T_2 > T_3 > T_4 > T_9 > T_6 > T_8 > T_1$. The iron content in T_2 (861.76 mg kg^{-1}) was on par with T_7 (862.87 mg kg^{-1}). The highest iron content in plant was observed in rice grown under T_5 (883.21 mg kg^{-1}): soil test based nutrient recommendation + vermicomposted rice straw, and lowest in T_1 (686.24 mg kg^{-1}): absolute control.

At harvest stage, T_5 receiving combined applications of soil test based nutrient recommendation and vermicomposted rice straw recorded highest plant iron content (776.00 mg kg^{-1}) and lowest was in T_1 (548.96 mg kg^{-1}) without any nutrients i.e., absolute control. The effect of various treatments on iron content at harvest followed the order: $T_5 > T_7 > T_9 > T_2 > T_3 > T_4 > T_6 > T_8 > T_1$. However, T_2 (707.30 mg kg^{-1}) was on par with T_9 (708.00 mg kg^{-1}).

4.3.5.8. Manganese

The magnesium content of plant at different stages of rice is given in Table 4.60.

Table 4.60: Effect of treatments on manganese content (mg kg^{-1}) in rice

Treatments	**Manganese content (mg kg^{-1})**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	188.78^{h}	155.13^{g}	108.86^{h}
T_2	286.00^{c}	196.18^{c}	121.56^{d}
T_3	204.30^{d}	192.00^{d}	119.67^{e}
T_4	200.62^{e}	191.13^{d}	117.78^{f}
T_5	296.00^{a}	204.08^{a}	167.78^{a}
T_6	196.93^{f}	190.79^{d}	111.07^{g}
T_7	292.00^{b}	200.05^{b}	155.40^{b}
T_8	192.25^{g}	160.60^{f}	109.97^{gh}
T_9	195.90^{f}	185.40^{e}	152.20^{c}
CD (0.05)	1.17	2.95	1.34

At tillering stage, highest manganese content (296.00 mg kg^{-1}) was observed in rice grown under T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and lowest (188.78 mg kg^{-1}) in T_1 (absolute control). The effect of treatments on manganese content catched the order: $T_5 > T_7 > T_2 > T_3 > T_4 > T_6 > T_9 > T_8 > T_1$. However, T_9 statistically on par with T_6 in plant manganese content at tillering stage of rice.

At panicle initiation stage of rice, manganese content varied from 155.13 to 204.08 mg kg^{-1}with lowest in T_1 (absolute control) and highest in T_5 (204.08 mg kg^{-1}). The effect of treatments on manganese content of rice followed the order: $T_5 > T_7 > T_2 > T_3 > T_4 > T_6 > T_9 > T_8 > T_1$. The manganese content of rice grown under T_6, T_4, and T_3 are statistically on par.

The manganese content in rice varied from 108.86 to 167.78 mg kg^{-1} at harvest with lowest in T_1 (absolute control) and highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw). However, manganese content of rice grown under T_8 (109.97 mg kg^{-1}) receiving combined applications of soil test based nutrient recommendation and rice husk was statistically on par with T_1. The effect of various treatments on manganese content of rice at harvest observed the order: $T_5 > T_7 > T_9 > T_2 > T_3 > T_4 > T_6 > T_8 > T_1$. The manganese content of rice grown under T_8 was on par with T_6.

4.3.5.9. Copper

The data on copper content in plant at different stages of rice after application of various treatments are furnished in Table 4.61.

Table 4.61: Effect of treatments on copper content (mg kg^{-1}) in rice

Treatments	Copper content (mg kg^{-1})		
	At tillering	Panicle initiation	Harvest
T_1	2.82^{d}	2.12^{f}	2.08^{f}
T_2	3.42^{a}	2.40^{c}	2.28^{c}
T_3	3.42^{a}	2.78^{b}	2.54^{b}
T_4	3.34^{ab}	2.33^{de}	2.50^{b}
T_5	3.43^{a}	3.25^{a}	3.09^{a}
T_6	3.25^{b}	2.30^{e}	2.17^{de}
T_7	3.40^{a}	2.36^{cd}	2.26^{c}
T_8	2.91^{cd}	2.17^{f}	2.10^{ef}
T_9	2.96^{c}	2.33^{de}	2.24^{cd}
CD (0.05)	0.09	0.06	0.09

Copper content at tillering stage varied from 2.82 to 3.43 mg kg^{-1}. However, T_1 was statistically on par with T_8. Copper content in rice grown under T_2, T_3, T_4, T_5 and T_7 were statistically on par. Similarly, copper content in T_8 and T_9 were also on par.

At panicle initiation stage copper content of rice varied from 2.12 to 3.25 mg kg^{-1}with lowest in T_1 (absolute control) and highest in T_5 (soil test based nutrient recommendation +

vermicomposted rice straw @ 5t ha^{-1}). Copper content in rice grown under T$_8$ was on par with T$_1$.

At harvest, copper content of rice varied from 2.08 to 3.09 mg kg^{-1}with lowest in T$_1$: absolute control and highest in T$_5$ (soil test based nutrient recommendation + vermicomposted rice straw @ 5t ha^{-1}).

4.3.5.10. Zinc

The effect of treatments on zinc content of plant at different stages of rice is given in Table 4.62.

At tillering, zinc content of plant varied from 43.50 to 55.10 mg kg^{-1} with lowest in T$_1$ (absolute control) and highest in T$_5$ (soil test based nutrient recommendation+ vermicomposted rice straw). However, zinc content in rice grown under T$_2$ (Adhoc organic KAU POP) was statistically on par with T$_5$. Similarly, zinc content in T$_8$ was on par with T$_1$.

Table 4.62: Effect of treatments on zinc content (mg kg^{-1}) in rice

Treatments	Zinc content (mg kg^{-1})		
	At tillering	Panicle initiation	Harvest
T$_1$	43.50^{f}	33.50^{d}	24.90^{g}
T$_2$	54.90^{a}	48.93^{a}	34.04^{b}
T$_3$	50.98^{bc}	43.20^{b}	29.50^{cd}
T$_4$	50.07^{cd}	39.10^{c}	28.48^{e}
T$_5$	55.10^{a}	49.23^{a}	34.95^{a}
T$_6$	49.17^{d}	38.19^{c}	26.90^{f}
T$_7$	52.18^{b}	44.76^{b}	29.95^{c}
T$_8$	44.17^{ef}	33.80^{d}	26.83^{f}
T$_9$	45.06^{e}	34.09^{d}	29.15^{d}
CD (0.05)	1.47	2.17	0.58

At panicle initiation stage, zinc content of various treatments varied from 33.50 to 49.23 mg kg^{-1}with lowest in T$_1$ (absolute control) and highest in T$_5$ (soil test based nutrient recommendation + vermicomposted rice straw). The zinc content in rice grown under T$_2$

(48.93 mg kg^{-1}) was statistically on par with T_5. The zinc content of T_8 (33.80 mg kg^{-1}) and T_9 (34.09 mg kg^{-1}) are statistically on par with T_1.

At harvest, zinc content of rice varied from 24.09 to 34.95 mg kg^{-1}with lowest in T_1 (absolute control) and highest in T_5 (soil test based nutrient recommendation+ vermicomposted rice straw).

4.3.5.11. Boron

The effect of treatments on boron content of plant at different growth stages of rice are presented in Table 4.63.

At tillering stage, rice grown under treatment T_2 receiving Adhoc organic KAU POP recorded highest boron content (4.18 mg kg^{-1}) and the lowest (3.31 mg kg^{-1}) was in T_1 (absolute control). The boron content in rice grown under T_6 (3.42 mg kg^{-1}): soil test based nutrient recommendation + rice husk biochar, T_9 (3.39 mg kg^{-1}): soil test based nutrient recommendation + rice straw, T_8 (3.35 mg kg^{-1}): soil test based nutrient recommendation + rice husk are statistically on par with T_1.

Table 4.63: Effect of treatments on boron content (mg kg^{-1}) in rice

Treatments	Boron content (mg kg^{-1})		
	At tillering	Panicle initiation	Harvest
T_1	3.26^{f}	3.17^{e}	3.13^{e}
T_2	3.28^{f}	3.26^{e}	3.20^{e}
T_3	3.62^{bc}	5.54^{b}	5.48^{b}
T_4	3.77^{a}	5.74^{a}	5.68^{a}
T_5	3.75^{ab}	5.64^{ab}	5.62^{a}
T_6	3.52^{cd}	5.05^{c}	4.96^{c}
T_7	3.42^{de}	5.04^{c}	4.93^{c}
T_8	3.35^{ef}	4.23^{d}	4.16^{d}
T_9	3.39^{def}	4.31^{d}	4.20^{d}
CD (0.05)	0.14	0.11	0.08

At panicle initiation stage, boron content in rice varied from 3.17 to 5.74 mg kg^{-1}. The highest boron content was observed in T_4 (soil test based nutrient recommendation+

vermicomposted rice husk) and it was on par with T_5 (soil test based nutrient recommendation+ vermicomposted rice straw). The lowest boron content was recorded by T_1 (absolute control) and T_2 (Adhoc KAU organic POP).

At harvest, highest boron content was observed in T_4 (5.68 mg kg^{-1}) and it was statistically on par with T_5 (5.62 mg kg^{-1}). The lowest boron content was observed in rice grown under T_1 (3.13 mg kg^{-1}) and it was statistically on par with T_2 (3.20 mg kg^{-1}).

4.3.5.12. Silicon

Silicon content in plant at tillering was found to be highest in T_6 (3.92 %). However, T_7 (3.90 %) was found to be statistically on par with T_6. The lowest plant silicon content was observed in rice grown under T_1 (3.51 %). However, T_3 and T_2 with silicon content of 3.52 per cent are statistically on par with T_1 (Table 4.64).

At panicle initiation stage, plants grown under treatment T_6 recorded highest silicon content (4.81 %). However silicon content in treatments T_7 (4.76 %), T_4 (4.72 %), and T_5 (4.75 %) were statistically on par with T_6. The lowest plant silicon content was recorded in rice grown under treatment T_1 (3.71 %) and it was statistically on par with T_2 and T_3 with 3.72 per cent silicon.

Table 4.64: Effect of treatments on silicon content (%) in plant

Treatments	**Silicon content (%)**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	3.51^{e}	3.71^{d}	3.28^{f}
T_2	3.52^{e}	3.72^{d}	3.29^{f}
T_3	3.52^{e}	3.72^{d}	3.28^{f}
T_4	3.86^{c}	4.72^{a}	4.13^{c}
T_5	3.88^{bc}	4.75^{a}	4.36^{b}
T_6	3.92^{a}	4.81^{a}	4.47^{a}
T_7	3.90^{ab}	4.76^{a}	4.41^{ab}
T_8	3.65^{d}	3.89^{c}	3.66^{e}
T_9	3.67^{d}	4.17^{b}	3.77^{d}
CD (0.05)	0.02	0.13	0.07

At harvest, highest silicon content was observed in rice grown under treatment T_6 (4.47 %). However, T_7 (4.41 %) was statistically on par with T_6. Statistically lowest plant silicon was observed in rice grown under T_1 and T_3 with 3.28 per cent Si and T_2 with 3.29 per cent silicon.

4.3.6. Biometric observations

4.3.6.1. Plant height

Plant height was significantly influenced by the treatment application at different growth stages of rice and the data are presented in Table 4.65. The plant height was significantly higher in all the treatments in comparison to absolute control (T_1).

At tillering, maximum plant height was produced in T_5 (66.33cm). However, plant height in T_2 (66.00 cm) was on par with T_5. Similar trend was observed in panicle initiation as well as at harvest. Plant height produced by T_5 and T_2 at panicle initiation stage was 143.54 and 141.00 cm, respectively. The plant height produced by T_5 and T_2 at harvest was 175.54 and 172.68 cm, respectively.

Table 4.65 : Effects of treatments on plant height

Treatments	**Plant height (cm)**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	58.44^{c}	100.33^{e}	128.33^{f}
T_2	66.00^{a}	141.00^{ab}	172.68^{ab}
T_3	62.03^{b}	137.03^{b}	168.03^{b}
T_4	61.90^{b}	136.90^{b}	166.92^{b}
T_5	66.33^{a}	143.54^{a}	175.54^{a}
T_6	60.66^{bc}	121.38^{c}	151.40^{cd}
T_7	60.41^{bc}	124.56^{c}	154.62^{c}
T_8	59.61^{bc}	115.03^{d}	139.66^{e}
T_9	59.77^{bc}	120.08^{d}	147.24^{d}
CD (0.05)	3.38	6.21	6.57

4.3.6.2. Number of tillers per hill

The total number of tillers produced per hill at various stage of crop are furnished in Table 4.66.

At tillering, highest number of tillers was produced in T_5 receiving vermicomposted rice straw and soil test based nutrient recommendation (23.60 tillers per hill). However, T_4, T_3, and T_2 were on par with T_5. The lowest number of tillers (14.66 tillers per hill) was produced by T_1 (absolute control).

Table 4.65 : Effects of treatments on number of tillers per hill

Treatments	**Number of tillers per hill**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	14.66^{e}	14.00^{d}	11.33^{e}
T_2	23.30^{a}	17.33^{b}	17.00^{ab}
T_3	23.00^{a}	17.00^{b}	16.33^{b}
T_4	22.66^{a}	17.00^{b}	15.55^{bc}
T_5	23.60^{a}	19.12^{a}	18.33^{a}
T_6	18.00^{d}	16.33^{bc}	14.33^{cd}
T_7	19.30^{cd}	16.33^{c}	14.33^{cd}
T_8	20.00^{bc}	15.44^{c}	13.06^{de}
T_9	21.30^{b}	15.92^{bc}	14.00^{cd}
CD (0.05)	1.30	1.44	1.85

The maximum number of tillers produced at panicle initiation stage was in T_5 (19.12 tillers per hill) and it was lowest in T_1 (14.00 tillers per hill).

At harvest, highest number of tillers was produced by treatments T_5 receiving vermicomposted rice straw and soil test based nutrient recommendation (18.33 tillers per hill). The lowest number of tillers produced at harvest was T_1 (11.33 tillers per hill). However, the tiller count in T_8 (13.06 tillers per hill) was statistically on par with T_1.

4.3.6.3. Dry matter production

The dry matter production obtained at various crop growth stages are presented in Table 4.67. Significant variation in dry matter production was observed among the treatments at various stages of rice.

At tillering, dry matter production was found to be highest in T_5 (7666.66 kg ha^{-1}) receiving vermicomposted rice straw and soil test based nutrient recommendation. The lowest dry matter content of 1830.67 kg ha^{-1} was observed in T_1 (1830.67 kg ha^{-1}). Dry matter production in various treatments at tillering followed the order: $T_5 > T_2 > T_3 > T_4 > T_7 > T_9 > T_8 = T_6 > T_1$.

Table 4.67: Effect of treatments on dry matter production

Treatments	**Dry matter production (kg ha^{-1})**		
	At tillering	**Panicle initiation**	**Harvest**
T_1	1830.67^{g}	10283.68^{i}	16003.58^{i}
T_2	7000.00^{b}	15650.33^{b}	24333.33^{b}
T_3	6666.66^{c}	15033.00^{c}	23500.00^{c}
T_4	6000.00^{d}	14333.33^{d}	23000.00^{d}
T_5	7666.66^{a}	16869.34^{a}	25333.00^{a}
T_6	3000.00^{f}	12750.00^{f}	21000.67^{f}
T_7	3368.67^{e}	13333.33^{e}	21650.00^{e}
T_8	3000.00^{f}	12029.36^{h}	19050.52^{h}
T_9	3333.33^{e}	12485.09^{g}	20589.00^{g}
CD (0.05)	204.03	75.55	62.35

At panicle initiation stage, the highest dry matter production was observed in T_5 (16869.34 kg ha^{-1}) and lowest in T_1 (10283.68 kg ha^{-1}). Significant variation was observed among the treatments and it was in the order: $T_5 > T_2 > T_3 > T_4 > T_7 > T_6 > T_9 > T_8 > T_1$.

At harvest, the dry matter content of various treatments obeyed the order: $T_5 > T_2 > T_3 > T_4 > T_7 > T_6 > T_9 > T_8 > T_1$. The dry matter content in T_5 and T_1 were 25333.00 kg ha^{-1} and 16003.58 kg ha^{-1}, respectively.

4.3.7. Yield attributes and yield

4.3.7.1. Number of panicles/m^2

The number of panicles was highest in T_5 (281.89 panicles/m^2) that received vermicomposted rice straw and soil test based nutrient recommendation and lowest in T_1 (169.73 panicles/m^2) i.e. absolute control. Effect of treatments differed significantly and it was in the order: $T_5 > T_2 > T_3 > T_4 > T_6 > T_7 > T_9 > T_8 > T_1$ (Table 4.68).

4.3.7.2. Number of spikelets per hill

The effects of treatments on number of spikelets per hill are presented in Table 4.68. The maximum number of spikelets was produced in T_5 (56.38 spikelets per hill) receiving vermicomposted rice straw and soil test based nutrient recommendation and the minimum of 33.95 spikelets per hill was observed in absolute control (T_1). The number of spikelets of various treatments followed the order: $T_5 > T_2 > T_3 > T_4 > T_6 > T_7 > T_9 > T_8 > T_1$.

4.3.7.3. Number of filled grains per panicle

Data on the effect of various treatments on number of filled grains per panicle showed that the maximum of 97.83 filled grains was recorded in T_5 receiving vermicomposted rice straw and soil test based nutrient recommendation. The number of filled grains in various treatments obeyed the order: $T_5 > T_2 > T_4 > T_6 > T_3 > T_7 > T_9 > T_8 > T_1$.

4.3.7.4. Chaff percentage

Highest percentage of chaff (23.33 %) was observed in treatment T_1 (absolute control) and lowest (18.48 %) in T_5 receiving vermicomposted rice straw and soil test based nutrient recommendation. The chaff per cent of treatments catched the order: $T_1 > T_8 > T_9 > T_7 > T_3 > T_6 > T_4 > T_2 > T_5$.

4.3.7.5. Thousand grain weight

The maximum of 28.61 g thousand grain weight was recorded in T_5 (soil receiving vermicomposted rice straw and soil test based nutrient recommendation) and it was superior to all other treatments. However, the treatment T_3 (28.53 g) receiving joint application of FYM @ 5t ha^{-1} and soil test based nutrient recommendation was statistically on par with T_5.

Table 4.68: Effect of treatments on yield attributes

Treatments	Panicles/m^2	Spikelets/hill	Filled grain/panicle	Chaff (%)	1000 grain weight (g)
T_1	169.73^{g}	33.95^{g}	92.00^{e}	23.33^{a}	26.00^{g}
T_2	276.72^{b}	55.34^{b}	96.52^{b}	19.57^{d}	28.05^{b}
T_3	276.62^{b}	55.32^{b}	95.05^{c}	20.79^{c}	28.53^{a}
T_4	276.05^{bc}	55.21^{bc}	95.56^{c}	20.37^{c}	27.92^{c}
T_5	281.89^{a}	56.38^{a}	97.83^{a}	18.48^{e}	28.61^{a}
T_6	275.76^{c}	55.15^{c}	95.54^{c}	20.38^{c}	27.86^{c}
T_7	273.23^{d}	54.65^{d}	93.92^{d}	21.73^{b}	27.57^{d}
T_8	246.90^{f}	49.38^{f}	93.63^{d}	21.98^{b}	26.56^{f}
T_9	268.97^{e}	53.79^{e}	93.85^{d}	21.79^{b}	27.98^{bc}
CD (0.05)	0.84	0.17	0.60	0.50	0.12

4.3.7.6. Grain yield

The effect of various treatments on grain yield was studied and the yield of each treatment in kg ha^{-1} are presented in Table 4.69.

The maximum grain yield of 7490 kg ha^{-1}was recorded in the treatment which received vermicomposted rice straw @ 5t ha^{-1}and soil test based nutrient recommendation (T_5). The lowest grain yield was obtained in absolute control (T_1) with a yield of 3826 kgha^{-1}. Significant variation in yield was observed among various treatments. The grain yield of various treatments followed the order: $T_5 > T_3 > T_2 > T_4 > T_6 > T_7 > T_9 > T_8 > T_1$.

Table 4.69: Effect of treatments on grain yield

Treatments	**Grain yield (kg ha^{-1})**
T_1	3826^{f}
T_2	7006^{c}
T_3	7175^{b}
T_4	6872^{c}
T_5	7490^{a}
T_6	6740^{d}
T_7	6718^{d}
T_8	6345^{e}
T_9	6702^{d}
CD (0.05)	149.21

4.3.7.7. Straw yield

Straw yield differed significantly among treatments and the data recorded are presented in Table 4.70. The highest straw yield (14510 kg ha^{-1}) was observed in the plots which were applied with vermicomposted rice straw @ 5t ha^{-1} and soil test based nutrient recommendation (T_5). Absolute control (T_1) recorded lowest straw yield (6098 kg ha^{-1}).

Table 4.70: Effect of treatments on straw yield

Treatments	Straw yield (kg ha^{-1})
T_1	6098^{i}
T_2	13420^{b}
T_3	13215^{c}
T_4	12810^{d}
T_5	14510^{a}
T_6	12314^{f}
T_7	12490^{e}
T_8	10375^{h}
T_9	11582^{g}
CD (0.05)	129.47

4.3.8. Nutrient uptake

The total uptake of nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, manganese, copper, zinc, boron and silicon by rice at harvest are presented in Table 4.71.

The data from Table 4.71 revealed that total nitrogen uptake by rice at harvest was found to be highest in treatment T_5 (141.86 kg ha^{-1}) receiving vermicomposted rice straw and soil test based nutrient recommendation and lowest in T_1 with an uptake of 60.81 kg ha^{-1} (absolute control).

Phosphorus uptake was found to be significantly higher in the treatment T_5 containing soil test based nutrient recommendation + vermicomposted rice straw (50.67 kg ha^{-1}). However, phosphorus uptake was lower in absolute control (T_1) and it was 18.67 kg ha^{-1}.

With respect to the potassium, the highest uptake was noted in T_5 (soil test based nutrient recommendation + vermicomposted rice straw) and it was 280.35 kg ha^{-1}. Significantly, lowest uptake value of 74.47 kg ha^{-1} was recorded in T_1 (absolute control).

Table 4.71: Effect of treatments on nutrient uptake

Treatments	Uptake (kg ha^{-1})											
	N	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Si**
T_1	60.81^{g}	18.67^{f}	74.47^{g}	13.17^{i}	2.70^{i}	9.74^{h}	8.78^{h}	1.74^{i}	0.398^{h}	0.033^{g}	0.089^{i}	524.92^{g}
T_2	126.53^{b}	46.23^{b}	253.07^{b}	21.81^{b}	7.37^{b}	16.09^{c}	17.21^{b}	2.96^{d}	0.828^{b}	0.058^{c}	0.149^{d}	800.57^{d}
T_3	117.50^{c}	42.30^{bc}	244.40^{b}	21.03^{c}	6.60^{c}	16.88^{b}	16.33^{c}	2.81^{e}	0.693^{c}	0.061^{b}	0.154^{c}	770.80^{e}
T_4	117.30^{c}	41.40^{c}	165.60^{e}	20.89^{d}	5.43^{e}	16.86^{b}	14.58^{e}	2.71^{f}	0.655^{d}	0.058^{c}	0.183^{b}	949.90^{bc}
T_5	141.86^{a}	50.67^{a}	280.35^{a}	23.77^{a}	7.80^{a}	18.83^{a}	19.66^{a}	4.25^{a}	0.885^{a}	0.075^{a}	0.189^{a}	1104.52^{a}
T_6	94.50^{de}	33.60^{d}	180.61^{d}	19.04^{f}	4.59^{g}	15.18^{e}	12.66^{f}	2.33^{g}	0.565^{f}	0.046^{e}	0.126^{f}	938.73^{c}
T_7	99.59^{d}	34.64^{d}	249.70^{b}	19.88^{e}	5.95^{d}	15.32^{d}	15.83^{d}	3.36^{b}	0.648^{d}	0.049^{d}	0.134^{e}	954.77^{b}
T_8	76.20^{f}	28.58^{e}	100.97^{f}	16.68^{h}	3.66^{h}	11.79^{g}	10.83^{g}	2.10^{h}	0.511^{g}	0.040^{f}	0.107^{h}	697.25^{f}
T_9	88.53^{e}	32.94^{d}	214.12^{c}	18.75^{g}	5.11^{f}	14.47^{f}	14.58^{e}	3.13^{c}	0.600^{e}	0.046^{e}	0.117^{g}	776.17^{e}
CD (0.05)	8.01	4.01	8.72	0.06	0.10	0.09	0.08	0.03	0.017	0.002	0.003	13.27

Uptake of calcium by rice receiving different treatments varied significantly. The calcium uptake was significantly higher in soil added with combined application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) than the other treatments (23.77 kg ha^{-1}). Calcium uptake was lowest in absolute control (T_1) and it was 13.17 kg ha^{-1}.

The data further revealed that there was significant difference between the treatments with respect to the uptake of magnesium. The magnesium uptake was found to be higher in T_5 receiving conjoint application of soil test based nutrient recommendation and vermicomposted rice straw (7.80 kg ha^{-1}).Uptake of magnesium was lower in T_1 (2.70kgha^{-1}).

Significantly higher sulphur uptake was recorded in T_5 (18.83 kg ha^{-1}). As could be expected, the uptake of sulphur was found to be lowest in T_1 (9.74 kg ha^{-1}).

As regards to the iron uptake by crop, soil test based nutrient recommendation + vermicomposted rice straw (T_5) registered higher value (19.66 kg ha^{-1}). The lowest uptake of iron was found in absolute control (T_1) and it was 8.78 kg ha^{-1}.

Significantly higher manganese uptake (4.25 kg ha^{-1}) was noticed in T_5 (soil test based nutrient recommendation + vermicomposted rice straw). However, the lowest uptake of 1.74 kg ha^{-1} was recorded in T_1 (absolute control).

The data shown in Table 4.71 showed that, copper uptake by crop differed significantly due to treatments. Highest copper uptake was noticed in T_5 soil test based nutrient recommendation + vermicomposted rice straw with a value of 0.075 kg ha^{-1}. Lowest uptake of copper by crop was noticed in absolute control (T_1) and it was 0.033 kg ha^{-1}.

The data on zinc uptake by crop showed a significant difference among treatments. The uptake of zinc was higher in T_5 (0.885 kg ha^{-1}) and lower in absolute control (0.398 kg ha^{-1}).

Total uptake of boron differed significantly due to treatments. Significantly highest uptake was noticed in T_5 (0.189 kg ha^{-1}). The uptake of boron was lowest in absolute control (0.089 kg ha^{-1}) than all other treatments.

The data given in Table 4.71 showed that silicon uptake by crop varied significantly due to treatment application. Highest silicon uptake was registered in T_5 (1104.52 kg ha^{-1}) and lowest in T_1 (524.92 kg ha^{-1}).

4.3.9. B: C ratio

The perusal data on B: C ratios of different treatments are given in Table 4.72. The highest B: C ratio of 2.43 was registered in T_5 (soil test based nutrient recommendation+ vermicomposted rice straw @ 5t ha^{-1}) followed by T_3 (soil test based nutrient recommendation+ FYM @ 5t ha^{-1}). The lowest B: C ratio (0.88) was observed in the treatment, absolute control (T_1).

Table 4.72: Effect of treatments on B: C ratio

Treatments	B:C ratio
T_1	0.88
T_2	2.15
T_3	2.28
T_4	2.19
T_5	2.43
T_6	1.78
T_7	1.44
T_8	1.92
T_9	2.02

4.3.10. Correlation studies

4.3.10.1. Correlation analysis between nutrient status of post-harvest soil and nutrient content in plant at harvest

The correlation coefficients (r) between nutrient *viz*., N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and Si status of post-harvest soil and nutrient content in plant at harvest were estimated and presented in Table 4.73. In the present study it was observed that nutrient content in soil and corresponding nutrient in plant at harvest maintained a highly significant and positive correlation.

Table 4.73: Coefficient of correlation between nutrient status of post-harvest soil and nutrient content in plant at harvest

Parameters	Correlation coefficient (r)
Soil-N and Plant-N	0.890^{**}
Soil-P and Plant-P	0.935^{**}
Soil-K and Plant-K	0.865^{**}
Soil-Ca and Plant-Ca	0.962^{**}
Soil-Mg and Plant-Mg	0.934^{**}
Soil-S and Plant-S	0.807^{**}
Soil-Fe and Plant-Fe	0.985^{**}
Soil-Mn and Plant-Mn	0.902^{**}
Soil-Zn and Plant-Zn	0.940^{**}
Soil-Cu and Plant-Cu	0.834^{**}
Soil-B and Plant-B	0.982^{**}
Soil-Si and Plant-Si	0.776^{*}

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

4.3.10.2. Correlation analysis between nitrogen fractions and plant nitrogen

The correlation analysis between nitrogen fractions in soil at tillering stage of rice and nitrogen content in plant are given in Table 4.74. The data showed that plant nitrogen had significant and positive correlation with total hydrolysable nitrogen (THN=0.873**), amino acid nitrogen (AAN=0.688*), ammoniacal nitrogen (AMN=0.886**), and nitrate nitrogen (NN=0.719*).

Table 4.74: Coefficient of correlation between nitrogen fractions and plant nitrogen at tillering

Parameters	THN	AAN	AMN	NN	Plant-N
THN	1				
AAN	0.715^{*}	1			
AMN	0.991^{**}	0.760^{*}	1		
NN	0.936^{**}	0.775^{*}	0.923^{**}	1	
Plant-N	0.873^{**}	0.688^{*}	0.886^{**}	0.719^{*}	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

The data in Table 4.75 revealed that nitrogen fractions had significant and positive correlation with plant nitrogen at panicle initiation stage of rice. Ammoniacal nitrogen had significant and positive correlation with total hydrolysable nitrogen (THN=0.993**) and amino acid nitrogen (AAN=0.787*).

Table 4.75: Coefficient of correlation between nitrogen fractions and plant nitrogen at panicle initiation

Parameters	THN	AAN	AMN	NN	Plant-N
THN	1				
AAN	0.758*	1			
AMN	0.993**	0.787*	1		
NN	0.954**	0.853**	0.959**	1	
Plant-N	0.754*	0.716*	0.785*	0.660^{NS}	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

4.3.10.3. Correlation analysis between phosphorus fractions and phosphorus content in plant

From the results of correlation analysis between phosphorus fractions in soil and phosphorus content in plant at tillering stage (Table 4.76) showed that soluble-P (0.958**), Fe-P (0.838**), Ca-P (0.734*), and organic-P (0.794*) had significant and positive correlation with plant-P.

The phosphorus content in plant at panicle initiation (Table 4.77) had significant and positive correlation with phosphorus fractions namely soluble-P (0.916**), Fe-P (0.896**), sesquioxide occluded-P (0.718*), Ca-P (0.736*), and organic-P (0.739*).

4.3.10.4. Correlation analysis between potassium fractions and potassium in plant

A review of data at tillering stage (Table 4.78) revealed that potassium content in plant had significant and positive correlation with water soluble-K (0.677*) and exchangeable-K (0.729*), and total-K (0.887**). Highly significant and positive correlation existed between water soluble-K and exchangeable-K (0.994**).

Table 4.76: Coefficient of correlation between phosphorus fractions and phosphorus content in plant at tillering

Parameters	Soluble-P	Al-P	Fe-P	Sesqui-P	Ca-P	Organic-P	Plant-P
Soluble-P	1						
Al-P	0.594^{NS}	1					
Fe-P	0.802**	0.882**	1				
Sesqui-P	0.561^{NS}	0.904**	0.788*	1			
Ca-P	0.756*	0.621^{NS}	0.682*	0.570^{NS}	1		
Organic-P	0.743*	0.756*	0.869**	0.843**	0.677*	1	
Plant-P	0.958**	0.616^{NS}	0.838**	0.590^{NS}	0.734*	0.794*	1

Table 4.77: Coefficient of correlation between phosphorus fractions and phosphorus content in plant at panicle initiation

Parameters	Soluble-P	Al-P	Fe-P	Sesqui-P	Ca-P	Organic-P	Plant-P
Soluble-P	1						
Al-P	0.646^{NS}	1					
Fe-P	0.812**	0.863**	1				
Sesqui-P	0.675*	0.840**	0.904**	1			
Ca-P	0.807**	0.646^{NS}	0.717*	0.599^{NS}	1		
Organic-P	0.795*	0.714*	0.811**	0.919**	0.713*	1	
Plant-P	0.916**	0.656^{NS}	0.896**	0.718*	0.736*	0.739*	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

Table 4.78: Coefficient of correlation between potassium fractions and potassium in plant at tillering

Parameters	WS-K	Ex-K	Plant-K
WS-K	1		
Ex-K	0.994**	1	
Plant-K	0.677*	0.729*	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

At panicle initiation stage (Table 4.79), plant-K had significant and positive correlation with water soluble-K (0.772*) and exchangeable-K (0.814*). Highly significant and positive correlation existed between water soluble-K and exchangeable-K (0.995**).

Table 4.79: Coefficient of correlation between potassium fractions and potassium in plant at panicle initiation

Parameters	WS-K	Ex-K	Plant-K
WS-K	1		
Ex-K	0.995**	1	
Plant-K	0.772*	0.814**	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

4.3.10.5. Correlation analysis between calcium fractions and calcium in plant

The correlation coefficient between calcium fractions in soil and calcium content in plant are given in Table 4.80. Plant calcium had highly significant and positive correlation with water soluble-Ca (0.910**) and exchangeable-Ca (0.928**).

Table 4.80: Coefficient of correlation between calcium fractions and calcium in plant at tillering

Parameters	WS-Ca	Ex-Ca	Plant-Ca
WS-Ca	1		
Ex-Ca	0.987**	1	
Plant-Ca	0.910**	0.928**	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

At panicle initiation (Table 4.81), plant-Ca had highly significant and positive correlation with water soluble-Ca (0.950**) and exchangeable-Ca (0.988**).

Table 4.81: Coefficient of correlation between calcium fractions and calcium in plant at panicle initiation

Parameters	**WS-Ca**	**Ex-Ca**	**Plant-Ca**
WS-Ca	1		
Ex-Ca	0.978**	1	
Plant-Ca	0.950**	0.988**	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

4.3.10.6. Correlation analysis between magnesium fractions and magnesium in plant

The magnesium content in plant at tillering (Table 4.82) had significant and positive correlation with water soluble magnesium (0.953**) and exchangeable magnesium (0.953**). Highly significant and positive correlation existed between exchangeable magnesium and water soluble magnesium (0.981**).

Table 4.82: Coefficient of correlation between magnesium fractions and magnesium in plant at tillering

Parameters	**WS-Mg**	**Ex- Mg**	**Plant- Mg**
WS-Mg	1		
Ex- Mg	0.981**	1	
Plant- Mg	0.953**	0.953**	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

At panicle initiation (Table 4.83), the magnesium content in plant had significant and positive correlation with water soluble magnesium (0.853**) in soil. The correlation between exchangeable magnesium and water soluble magnesium was highly significant and positive (0.977**).

Table 4.83: Coefficient of correlation between magnesium fractions and magnesium in plant at panicle initiation

Parameters	WS-Mg	Ex- Mg	Plant- Mg
WS-Mg	1		
Ex- Mg	0.977^{**}	1	
Plant- Mg	0.853^{**}	0.858^{**}	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

4.3.10.7. Correlation analysis between sulphur fractions and sulphur in plant

From the correlation studies (Table 4.84), it could be concluded that, the sulphur content in plant at tillering stage significantly and positively correlated with organic-S (0.692*) and available-S (0.891*). The available-S had significant and positive correlation with organic-S (0.889**)

Table 4.84: Coefficient of correlation between sulphur fractions and sulphur in plant at tillering

Parameters	Organic-S	Available-S	Plant-S
Organic-S	1		
Available-S	0.889^{**}	1	
Plant-S	0.692^{*}	0.891^{**}	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

From the correlation analysis between sulphur fractions and sulphur content in plant at panicle initiation (Table 4.85), it could be inferred that, the plant-S content had significant and positive correlation with organic-S (0.675*) and available-S (0.862**).The available-S had highly significant and positive correlation with organic-S (0.882**).

Table 4.85: Coefficient of correlation between sulphur fractions and sulphur in plant at panicle initiation

Parameters	Organic-S	Available-S	Plant-S
Organic-S	1		
Available-S	0.882^{**}	1	
Plant-S	0.675^{*}	0.862^{**}	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

4.3.10.8. Correlation analysis between silicon fractions and silicon in plant

From the correlation analysis between silicon fractions in soil at tillering stage and silicon content in plant, it could be concluded that (Table 4.86), silicon content in plant had highly significant and positive correlation with mobile-Si (0.870**), adsorbed-Si (0.982**), organic-Si (0.741*), occluded-Si (0.979**) and residual-Si (0.984**).

At panicle initiation stage, the plant silicon content was significantly and positively related with soil silicon fractions in soil (Table 4.87) *viz*., mobile-Si (0.923**), adsorbed-Si (0.984**), organic-Si (0.700*), occluded-Si (0.945**), and residual-Si (0.953**). The mobile-Si fraction in soil had significant and positive correlation with adsorbed-Si (0.971**), organic-Si (0.805**), occluded-Si (0.979**), and residual-Si (0.973**).

4.3.10.9. Correlation analysis between nutrient status of post-harvest soil and nutrient uptake at harvest

Organic carbon content of post-harvest soil and nutrient uptake had significant and positive correlation (Table 4.88). It was also observed that nutrient content in soil *viz*., N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B and Si as well as corresponding nutrient uptake by plant at harvest had significant and positive correlation.

Table 4.86: Coefficient of correlation between silicon fractions and silicon in plant at tillering

Parameters	Mobile-Si	Adsorbed-Si	Organic-Si	Occluded-Si	Residual-Si	Plant-Si
Mobile-Si	1					
Adsorbed-Si	0.927**	1				
Organic-Si	0.900**	0.786*	1			
Occluded-Si	0.925**	0.977**	0.840**	1		
Residual-Si	0.922**	0.984**	0.832**	0.997**	1	
Plant-Si	0.870**	0.982**	0.741*	0.979**	0.984**	1

Table 4.87: Coefficient of correlation between silicon fractions and silicon in plant at panicle initiation

Parameters	Mobile-Si	Adsorbed-Si	Organic-Si	Occluded-Si	Residual-Si	Plant-Si
Mobile-Si	1					
Adsorbed-Si	0.971**	1				
Organic-Si	0.805**	0.738*	1			
Occluded-Si	0.979**	0.973**	0.848**	1		
Residual-Si	0.973**	0.976**	0.791*	0.989**	1	
Plant-Si	0.923**	0.984**	0.700*	0.945**	0.953**	1

(*Correlation is significant at the 0.05 level   **Correlation is significant at the 0.01 level)

Table 4.88: Coefficient of correlation between nutrient status of post-harvest soil and nutrient uptake at harvest

Parameters	Correlation coefficient (r)
Soil-OC and N-uptake	0.676*
Soil-OC and P-uptake	0.684*
Soil-OC and K-uptake	0.736*
Soil-OC and Ca-uptake	0.783*
Soil-OC and Mg-uptake	0.674*
Soil-OC and S-uptake	0.800**
Soil-OC and Fe-uptake	0.701*
Soil-OC and Mn-uptake	0.671*
Soil-OC and Zn-uptake	0.669*
Soil-OC and Si-uptake	0.915**
Soil-N and N-uptake	0.895**
Soil-P and P-uptake	0.946**
Soil-K and K-uptake	0.807**
Soil-Ca and Ca-uptake	0.795*
Soil-Mg and Mg-uptake	0.951**
Soil-S and S-uptake	0.702*
Soil-Fe and Fe-uptake	0.911**
Soil-Mn and Mn-uptake	0.942**
Soil-Zn and Zn-uptake	0.944**
Soil-Cu and Cu-uptake	0.928**
Soil-B and B-uptake	0.804**
Soil-Si and Si-uptake	0.840**

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

4.3.10.10. Correlation analysis between biometric observations at harvest, yield attributes, and yield of rice

Grain yield had highly significant and positive correlation with tillers/hill (0.855**), plant height (0.867**), panicles/m^2 (0.986**), spikelets/hill (0.986**), filled grain/panicle (0.840**), and thousand grain weight (0.937**). Similarly, a highly significant and positive correlation existed between plant height, dry matter content and straw yield (Table 4.89).

Table 4.89: Correlation analysis between biometric observations at harvest, yield attributes, and yield

Parameters	**Correlation coefficient (r)**									
Tillers/hill	1									
Plant height	0.976^{**}	1								
Dry matter	0.982^{**}	0.989^{**}	1							
Panicles/m^2	0.770^{*}	0.795^{*}	0.858^{**}	1						
Spikelets/hill	0.770^{*}	0.795^{*}	0.858^{**}	1.000^{**}	1					
Filled grains/panicle	0.944^{**}	0.906^{**}	0.917^{**}	0.750^{*}	0.750^{*}	1				
Thousand grain weight	0.910^{**}	0.909^{**}	0.938^{**}	0.873^{**}	0.873^{**}	0.874^{**}	-0.875^{**}	1		
Grain yield	0.855^{**}	0.867^{**}	0.920^{**}	0.986^{**}	0.986^{**}	0.840^{**}	-0.840^{**}	0.937^{**}	1	
Straw yield	0.937^{**}	0.929^{**}	0.898^{**}	0.560^{NS}	0.560^{NS}	0.839^{**}	-0.839^{**}	0.762^{*}	0.662^{NS}	1

(*Correlation is significant at the 0.05 level **Correlation is significant at the 0.01 level)

DISCUSSION

5. DISCUSSION

Rice can be designated as the most important human food crop in the world, produced in a wide range of locations extending from wettest areas to the driest desserts. Rice cultivation involves accruement of large quantities of straw and stalk. The milling of paddy also yields large amount of husk or hull. These residues have immense potential for enhancing soil organic matter content. The production of biochar and composting of these residues are the effective and proven residue management strategies that have high potential to improve soil properties and crop productivity. Thermochemical decomposition of condensed substances by heating under oxygen controlled condition yields the product ‘biochar’. Vermicomposting is the mesophilic oxidative conversion of organic matter to mucus coated granular worm casts through the combined action of microorganisms and earthworms. This chapter justifies the results obtained from the project entitled “Nutrient dynamics and crop productivity in lowland lateritic soil (AEU 10) under rice residue management practices” with suitable illustrations and supporting literature.

5.1. CHARACTERIZATION OF RICE RESIDUES AND THEIR PRODUCTS

5.1.1. Yield

Vermicompost and biochar was prepared from the collected straw as well as husk and the yield obtained is depicted in Figure 5.1 which shows that the output from vermicomposting was more (74.38 % for VRS and 70.03 % for VRH) than when the residues were converted into biochar through pyrolysis.

Reports say that the biochar yield is highly dependent on the pyrolysis conditions such as temperature, heating rate and residence time (Uzun *et al.*, 2006; Tsai *et al.*, 2007) and is also greatly influenced by physical, chemical and biological properties of the raw materials used (Tanaka, 1963; Knoepp *et al*., 2005; Lehmann, 2007; Chan and Xu, 2009; Basta *et al*., 2011; Conz *et al*., 2017). Elangovan (2014) reported recovery percentage of 12 to 40, when pyrolysis was done using different biological residues. On an average, 19.86 per cent rice straw biochar (RSB) and 38.00 per cent rice husk biochar (RHB) could be recovered from the straw and husk, respectively. These results are in good agreement with earlier studies on this

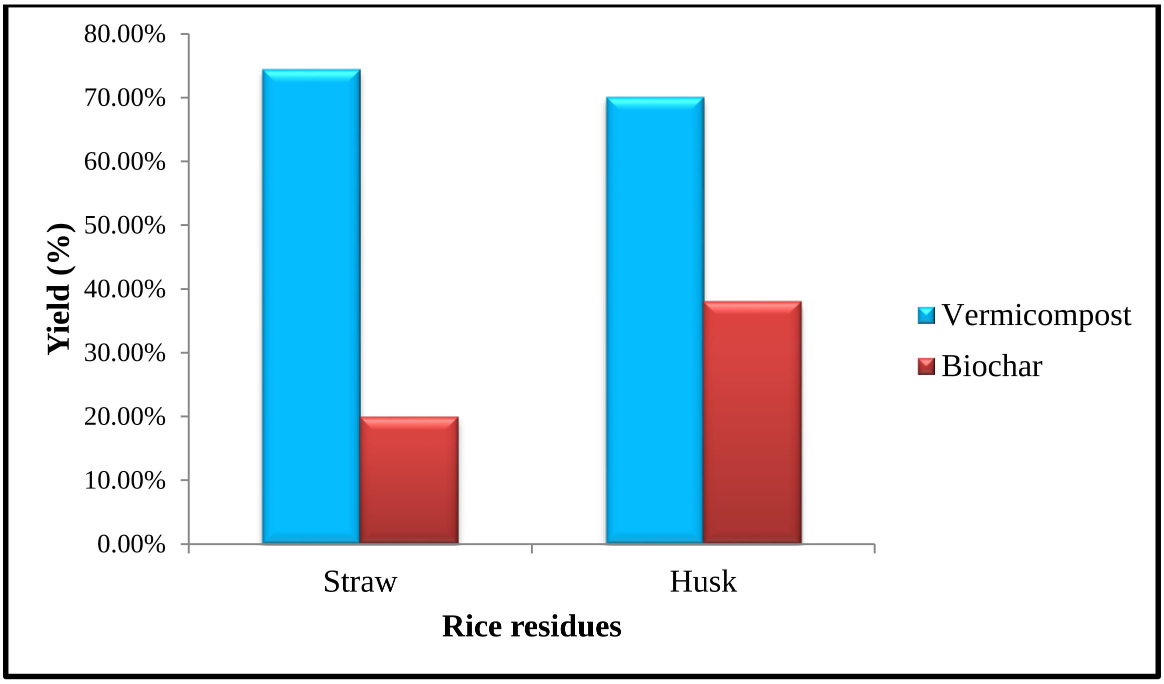


Fig.5.1: Yield of vermicompost and biochar from straw and husk

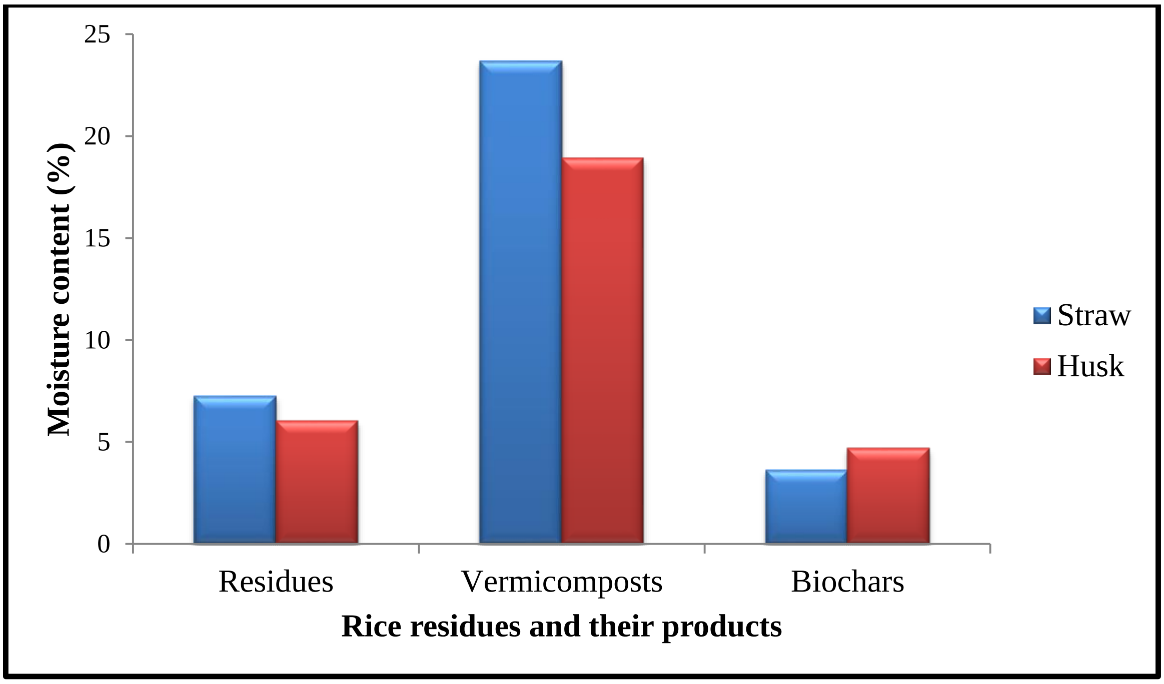


Fig. 5.2: Moisture content of rice residues and their products

line by Phuong *et al*. (2015), where they concluded that the decrease in biochar yield might be due to the thermal decomposition of organic material present in the residues.

Higher yield in RHB than RSB might be due to the high lignin content in the husk. Raveendran *et al*. (1995) and Nik-Azar *et al*. (1997) reported that greater the concentration of lignin, more was the recovery during pyrolysis.

5.1.2. Physical properties

Moisture content

The moisture content of residues and their products are portrayed in Figure 5.2. The moisture content of straw was higher (7.24 %) compared to husk (6.03 %). Rice straw usually has higher moisture content than the husks because straw is obtained during harvest. Unlike the husk which is separated from the dried paddy during milling process. This clearly indicates that different parts of the rice plant maintain different moisture content. Similar findings were also reported by Zhang *et al*. (2019), wherein straw reported high moisture content than husk in all the varieties tested.

Comparatively, higher moisture content was observed in VRS (23.68 %) than VRH (18.94 %). The variation in moisture content among the vermicomposts (VRS and VRH) might be due to the higher porosity of VRS.

Pyrolysis process reduced the moisture content of final product (biochar) than the raw materials. Among the produced biochars, RHB recorded highest moisture content (4.68 %) than RSB (3.62 %). These signified that biochar produced from rice straw showed better resistance to alter its moisture content when compared with the biochar produced from rice husk. This may be due to lower bulk density and highly porous nature of RHB. The results are in agreement with the findings of Deka *et al*. (2018). The potential of biochar with low bulk density, an indication of its highly porous nature and small particle size, in holding moisture has already been reported from the studies of Hernandez-Mena *et al.* (2010).

Colour, odour and particle size

Rice residues such as straw and husk were yellow in colour, whereas the resultant vermicompost from both the sources was brown in colour which might be due to the presence of humic substances in vermicompost. Similar findings were also reported by Thiyageshwari *et al*. (2018) from their studies on exploration of rice husk compost as alternate manure to enhance the productivity of black gram in Typic Haplustalf and Typic Rhodustalf. As the materials decomposed during vermicomposting, they would start to produce various organic acids that cause the colour change in final mature compost. Biochar produced are black in colour due to the high carbon content.

No foul odour was experienced from the residues and their products. Particle size determination following FCO specification revealed that 100 per cent of the composted material and biochar passing through 4 mm IS sieve.

Bulk density

The bulk density values of rice straws (0.80 Mg m^{-3}) were lower than those of rice husks (0.89 Mg m^{-3}). This might be due to the higher content of ash and lignin in the rice husk. Similar observation on bulk density has also been reported by Zhang *et al*. (2019).

The increase in particle size during vermicomposting due to the amalgamation of small particles resulted in reducing the bulk density of vermicomposts. Vermicomposted rice husk had comparatively lower bulk density (0.72 Mg m^{-3}) than vermicomposted rice straw (0.78 Mg m^{-3}). Higher particle size of VRH than VRS resulted in lower bulk density of VRH.

Pyrolysis process reduced the bulk density of raw materials and among the produced biochars, RSB showed comparatively higher bulk density (0.64 Mg m^{-3}) than RHB (0.59 Mg m^{-3}). This might be due to the lower particle size of the RSB than RHB. These results are in agreement with the findings of Deka *et al*. (2018), who reported that the bulk density of RSB was high compared to RHB.

The lower bulk density values of residues and products (Figure 5.3) compared to soil indicated its promising role in reducing the soil bulk density and increasing the porosity thus its capability to hold more water when applied to soil.

5.1.3. Electro-chemical properties

pH

pH is an important electro-chemical property controlling the availability of nutrients. Straw and husk are alkaline in nature, having a pH value 7.81 and 7.24, respectively (Figure 5.4). The variation in pH during vermicomposting depend on the chemical quality of

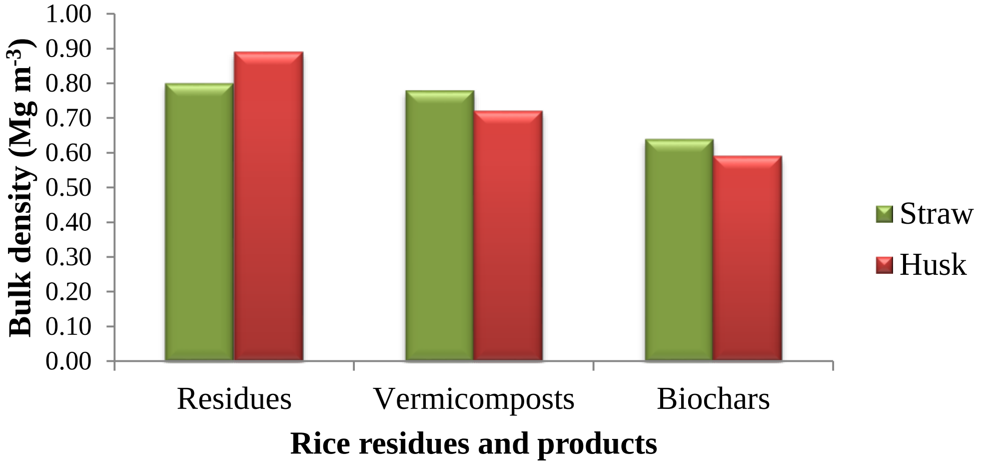


Fig. 5.3: Bulk density of rice residues and their products

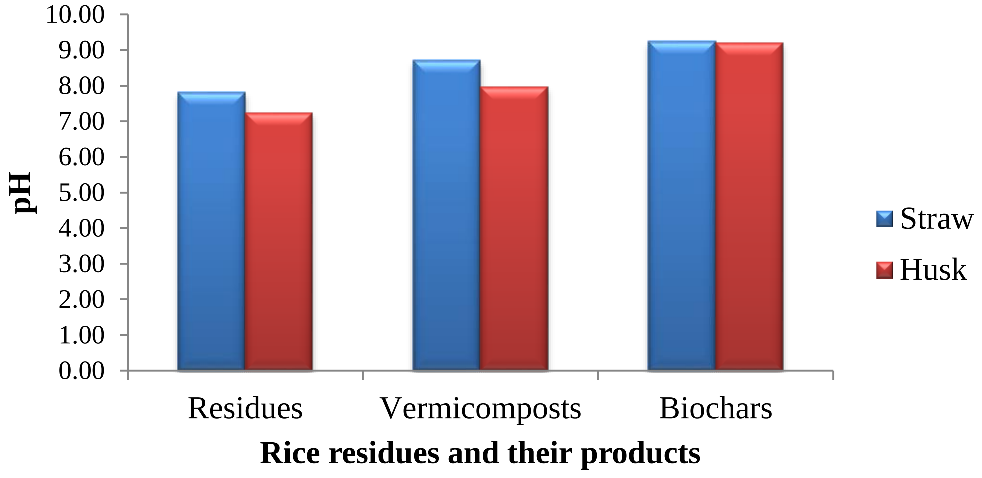


Fig. 5.4: pH of rice residues and their products

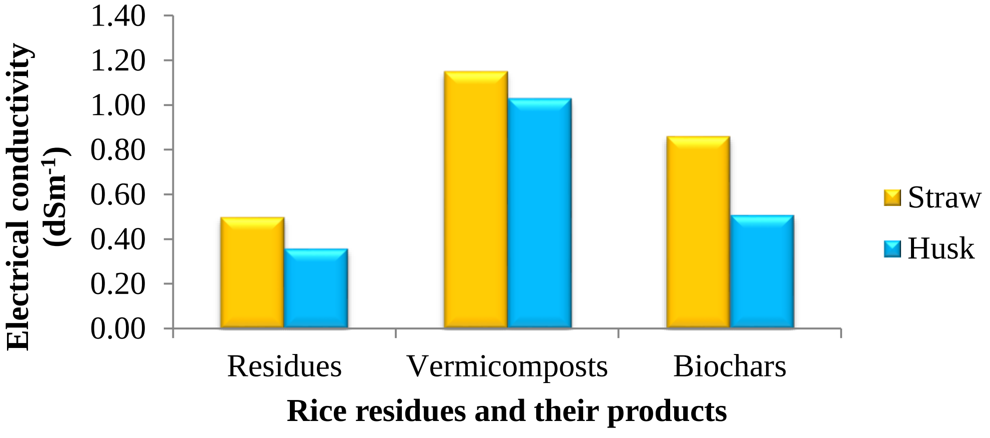


Fig. 5.5: Electrical conductivity of rice residues and their products

residues. The pH value of 8.71 and 7.97 associated with VRS and VRH revealed their alkaline nature. The increase in pH after vermicomposting probably resulted from the release of ammonia due to the proteolytic process. These results are in agreement with the findings of Thiyageshwari *et al*. (2018). High solubility of nutrients in earthworm casts could be another reason for the rise in pH in the present study.

The pH of biochars was comparatively higher than the initial residues as well as vermicomposts. This might be due to the production of alkali salts during pyrolysis process. At a higher temperature, the alkali salts begin to separate from the organic matrix thus increasing the pH consequently. Among the produced biochars, RSB having higher pH compared to RHB. So, alkalinity also highest in RSB compared to RHB. Highest pH recorded in RSB could be supported by high calcium and magnesium content in RSB as shown in the results of the present study. Similar results were also reported earlier by Wu *et al*. (2012) and Deka *et al*. (2018) while experimenting with rice straw and rice husk derived biochar.

Electrical conductivity

Electrical conductivity (EC) is a measure of concentration of soluble salts and higher EC indicated the higher accumulation of salts. Electrical conductivity of straw and husk was 0.50 dS m^{-1} and 0.36 dS m^{-1}, respectively (Figure 5.5). The higher electrical conductivity of straw might be due to the presence of soluble salts than the husk.

The present study revealed that electrical conductivity increased on vermicomposting. Decomposition of substrates and subsequent release of exchangeable bases would have increased electrical conductivity of the compost. In a study on composting using agricultural byproducts, Chandna *et al.* (2013) also reported an increase in initial substrate electrical conductivity on composting. Loss of biomass through the biotransformation of organic materials and subsequent mineralization of nutrient elements could have attributed to the increment in EC. Among the produced vermicomposts, VRS had higher EC (1.15 dS m^{-1}) than VRH (1.03 dS m^{-1}). This variation might be due to the presence of soluble salts in VRS.

The electrical conductivity of biochar was also higher than the residual biomass but comparatively lower than vermicomposts because of lower nutrient composition in biochar than compost. The RSB had higher EC (0.86 dS m^{-1}) than RHB (0.51 dS m^{-1}). This might be due to the higher ash content in RSB. Deka *et al*. (2018) also reported the similar trend in electrical conductivity of straw derived biochar as well as husk derived biochar.

5.1.4. Chemical properties

The chemical composition of straw and husk were studied and it was observed that straw was comparatively superior to the husk in respect of C, N, K, Ca, Mg, Fe, Mn, Cu, and Zn. Whereas, husk was superior in P, S, B, Si, cellulose and lignin. The process of vermicomposting helped to concentrate the nutrients *viz*., N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, B, and silicon and reduce the content of carbon, cellulose and lignin thereby narrowing down the C: N ratio. Conversion of residues into biochar also increases the nutrients *viz.*, P, K, and Si in the final product, while carbon as well as other nutrients, cellulose, and lignin content were found to be decreased after pyrolysis.

Carbon

After vermicomposting, carbon content of straw and husk got reduced remarkably due to the combined action of earthworm ingestion and decomposition by microbes (Figure 5.6). The content of C in compost is the major source of energy for the microorganisms. Comparatively lowest carbon reduction was noticed in the case of vermicomposting rice husk. This might be due to the incomplete decomposition of the husk even after vermicomposting as a result of high lignin content, suggesting that rice husk degrades very slowly.

The values on carbon content of biochar obtained from the present study revealed its highly carbonaceous nature than vermicompost. The increased carbon of biochar indicates that pyrolysis temperature promotes carbonization (Chun *et al*., 2004). This promotion was due to high degree of polymerization leading to more condensed carbon structure in the biochar (Lehmann and Joseph, 2009). The carbon content in biochar was slightly lower than the residues and it might be due to the loss of aliphatic carbon as a result of pyrolysis. Charring temperature decreases the aliphatic carbon groups while aromatic carbon became more dominant. The high carbon storage associated with biochar can be directly related with the high C content in the raw material (Lee *et al*., 2013).

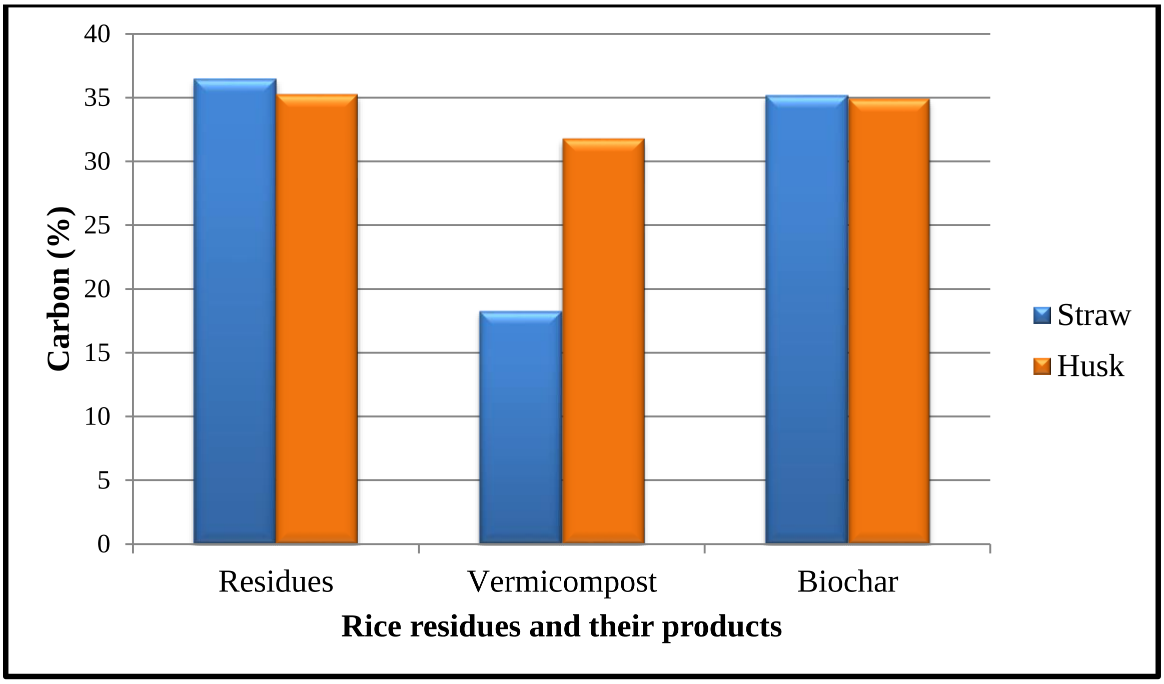


Fig. 5.6: Carbon content in rice residues and their products

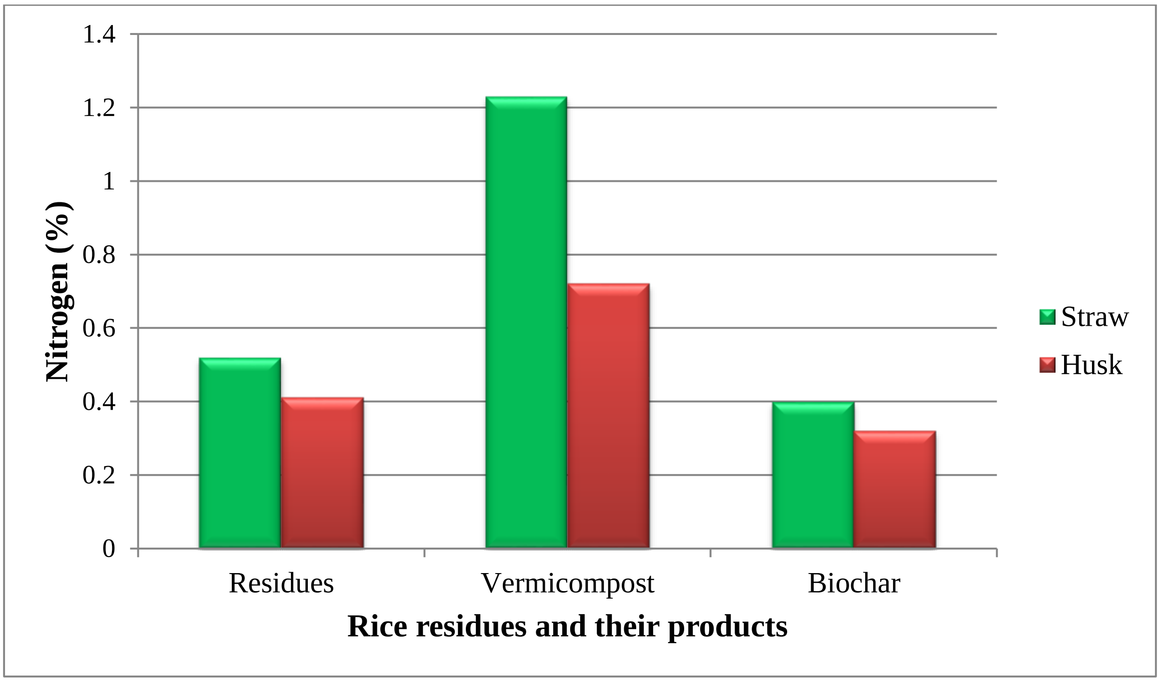


Fig. 5.7: Nitrogen content in residues and their products

Nitrogen

The increased N content of the compost is due to the mineralization of proteins present in the substrates to nitrate and ammoniacal forms. The nitrogen content in the cowdung also contributed to increase in total nitrogen of vermicompost. It is normally seen that when organic matter reduction is more than the loss of NH_3, nitrogen concentration usually increases. Among the produced vermicomposts, VRS recorded comparatively higher nitrogen than VRH (Figure 5.7). The highest nitrogen content in VRS might be due to higher nitrogen in straw.

Total nitrogen content was found to decrease with pyrolysis process and is evident from the FT-IR spectra of biochar. This might be due to the volatilization loss of nitrogen during pyrolysis. When plant biomass is subjected to pyrolysis, their N containing structures, *i.e.*, amino sugars, amino acids and amines, which are part of nitrogen, get transformed into heterocyclic N aromatic structures (Cao and Harris, 2010 and Koutcheiko *et al*., 2006). Among the biochars produced, RSB recorded highest value than RHB. This might be due to the high amount of nitrogen contained in straw which fully tally with the finding that nitrogen content of biochar strongly depends on the starting material in straw.

Phosphorus

The phosphorus content of the vermicomposts was higher than the residues (Figure 5.8). The phosphorus content in the residue as well as in cowdung might have contributed to increase in phosphorus in final vermicompost. The VRH had lower phosphorus than VRS, even though the husk had high P. This might be due to the incomplete decomposition or mineralization of husk during vermicomposting.

Mineralization and mobilization of phosphorus by bacterial and phosphatase activity of earthworms could be the main reason of phosphorus increase in vermicompost (Tripathi and Bhardwaj, 2004). When organic matter passes through the gut of earthworm, some phosphorus is converted into more available form. The release of phosphorus in the available form is performed partly by earthworm gut phosphatase and further release of phosphorus can be ascribed to the phosphorus solubilizing microorganisms present in the worm casts (Suthar, 2008).

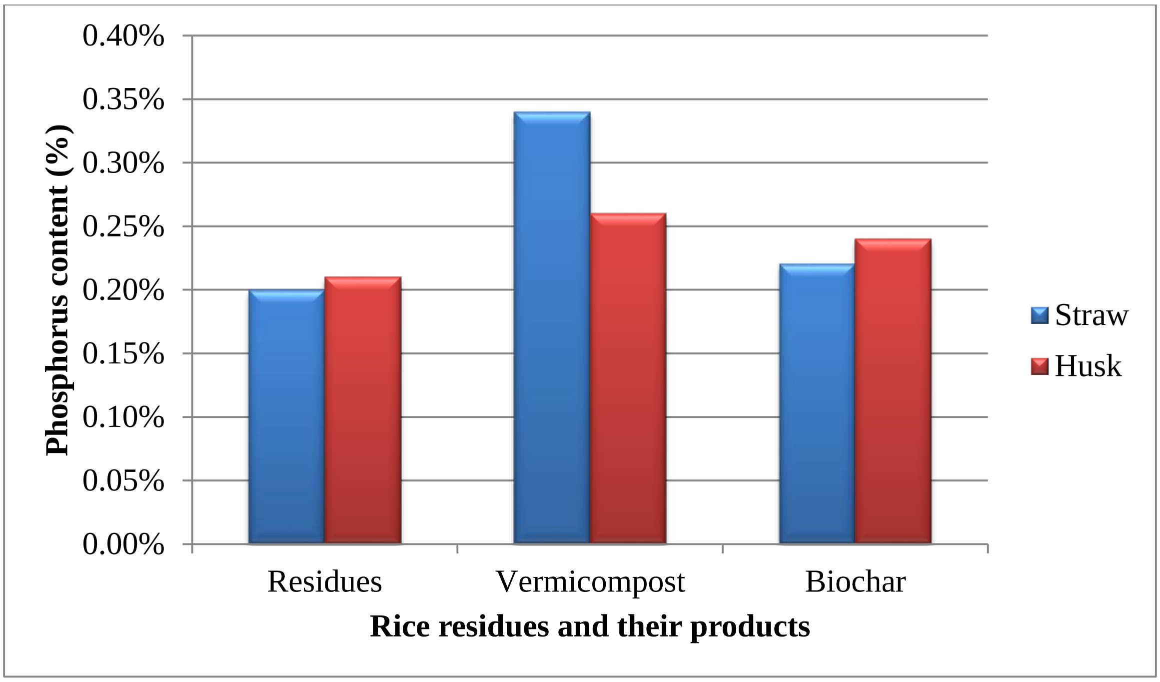


Fig. 5.8: Phosphorus content in rice residues and their products

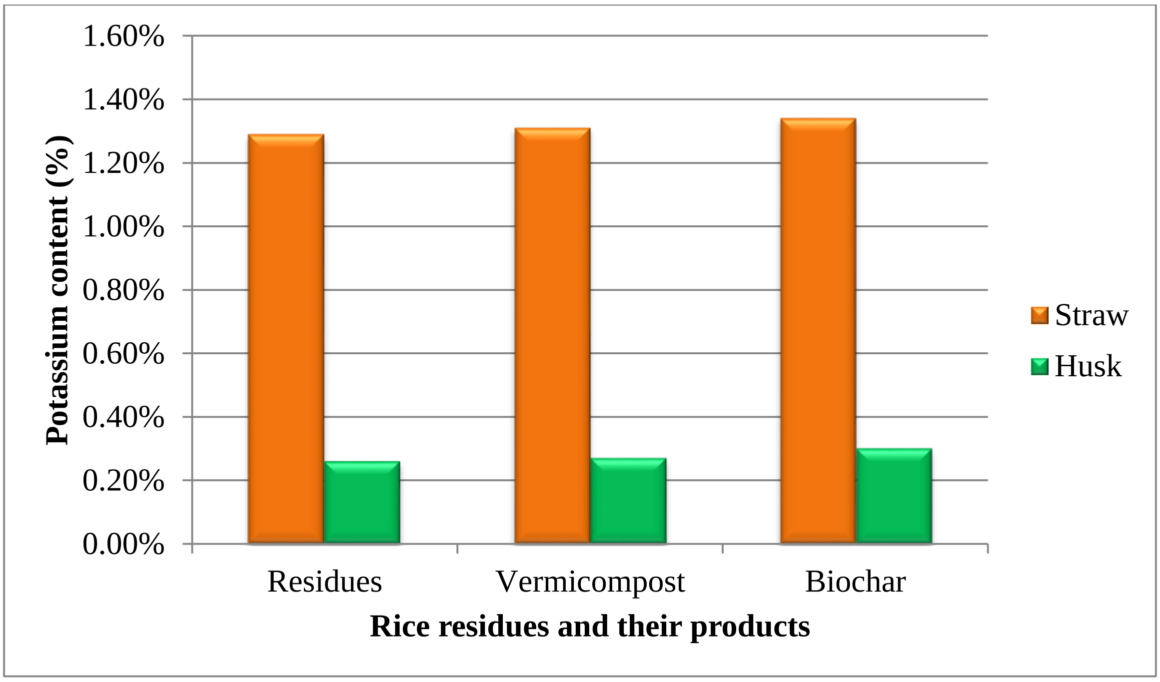


Fig. 5.9: Potassium content in rice residues and their products

Charring enhances P availability from residues. This is because with combustion, there is disproportionate volatilization of carbon which leads to cleavage of organic phosphorus bonds thus yielding biochar rich in soluble salts of phosphorous (Knoepp *et al*., 2005). Comparatively, higher phosphorus content was observed in RHB than RSB because of rice husk containing a higher proportion of phosphorus.

Potassium

Vermicompost had higher potassium content than the residues. The increase in potassium content in the vermicompost suggests that earthworms has symbiotic gut microflora with secreted mucus and water to increase the degradation of ingested substrates and release of metabolites (Khwairakpam and Bhargava, 2009).

The higher potassium content and complete decomposition of straw than the husk resulted in comparatively higher potassium in VRS than VRH (Figure 5.9). Chandna *et al*. (2013) also opined that during the composting of agricultural substrates, organic C decreased, whereas total N, P and K increased with time.

The nutrient content in biochar was comparatively lower than the vermicompost and residue. Whereas, the potassium content was found to be more in biochar. This might be due to the ash content present in the biochar. The potassium content was found to be highest in RSB than RHB. This might be due to the higher potassium content in straw.

Secondary nutrients

Comparatively higher calcium content was observed in straw than the husk (Figure 5.10). Upon vermicomposting of residues, calcium content was found to be increased. Calcium enrichment occurs when the substrates pass through the digestive tract of earthworms. Earthworms were reported to captivate Ca in excess from their food and transfer it to calciferous glands, which contain carbonic anhydrase enzyme which catalyse the fixation of CO_2 as $CaCO_3$ concretions before being excreted through the digestive tracts (Padmavathiamma *et al.,* 2008). The bicarbonates produced in excess of earthworm metabolic requirement were excreted as cast material, thus increasing the calcium content in the final vermicompost. The indistinguishable significance of composting and vermicomposting in enriching the compost with calcium content was earlier reported by Mayadevi (2016).

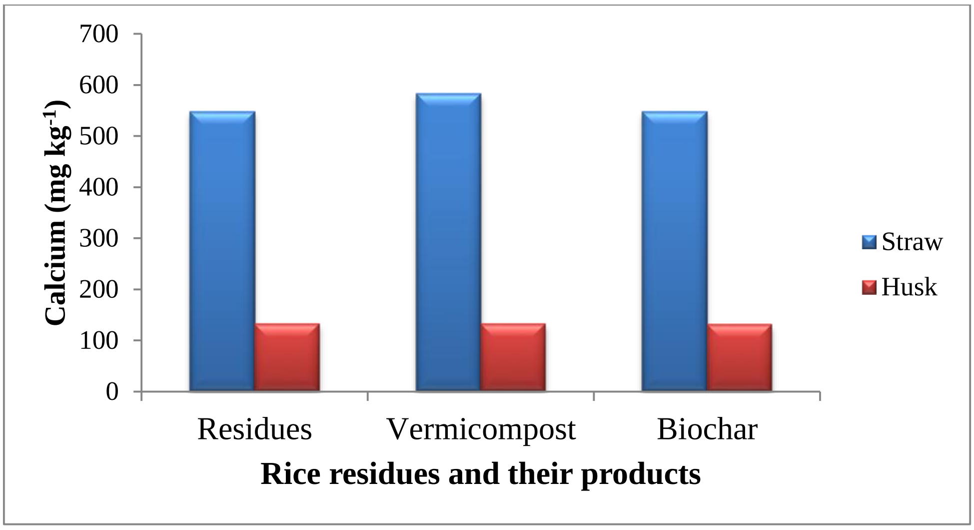


Fig.5.10: Calcium content in rice residues and their products

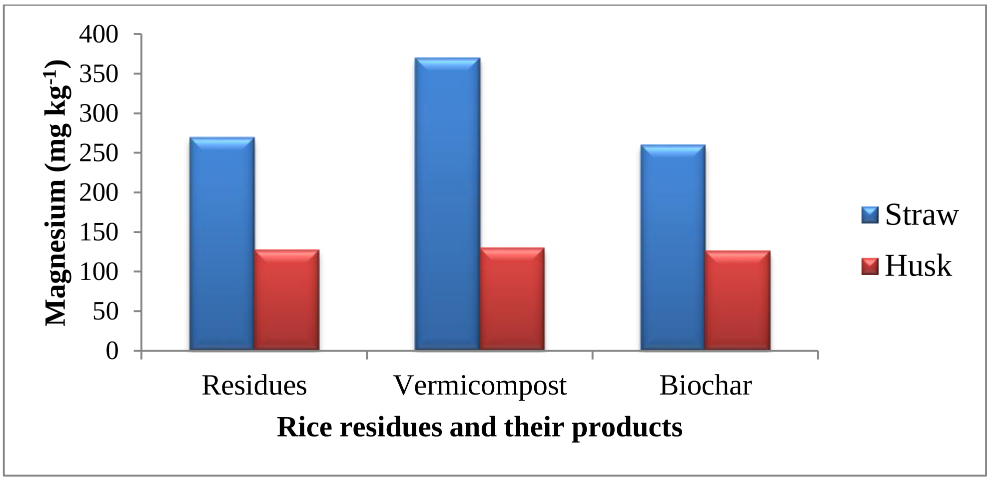


Fig. 5.11: Magnesium content in rice residues and their products

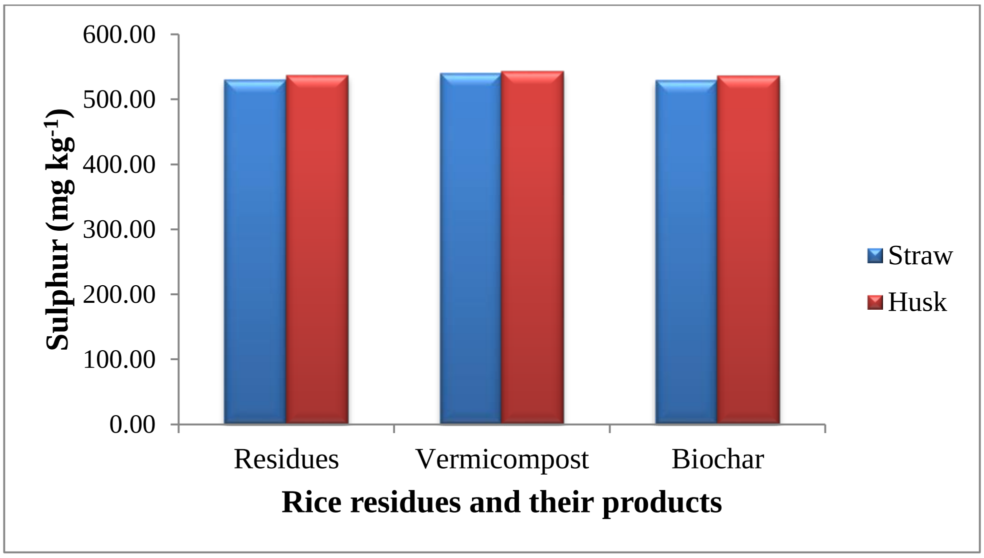


Fig.5.12: Sulphur content in rice residues and their products

Among the produced vermicomposts, VRS recorded higher calcium content than VRH. This might be due to higher calcium in rice straw than rice husk. The per cent increase in calcium was comparatively lower in VRH. This might be due to the incomplete decomposition of husk during vermicomposting. Pyrolysis process increases the calcium content in the final product. The increase in calcium content in the biochar might be due to the release of calcium during pyrolysis. Among the biochars produced, RSB had higher calcium content than RHB. This might be due to the higher calcium level in straw.

Among the rice residues, magnesium content was highest in straw than the husk. Their products also shows similar trend while content was found to higher than the residues in case of vermicompost and lower than residues in biochar (Figure 11). Among the products of residues, vermicompost recorded highest magnesium content compared to biochar.

Rice husk had comparatively higher sulphur content than straw. Only slight variation in sulphur content was observed among the residues and their products (Figure 12).

Micronutrients

Among the micronutrients, iron was found to be dominant in rice residues than the other micronutrients *viz*., manganese, copper, zinc, and boron (Figure 5.13-5.16). Straw was superior to rice husk with respect to all micronutrients except boron. Vermicomposting and go in favour of increasing micronutrient content in the final product. This might be due to the biological decomposition of residues during vermicomposting as well as the nutrients in FYM and residues.

Silicon

Silicon (Si) is considered as a beneficial element for crop growth, especially for crops under *Poaceae* family. Rice is a typical silicon accumulating plant and it benefits from silicon nutrition. Silicon increases the mechanical strength of the culm, thus reducing crop lodging (Savant *et al*., 1997). Silicon interacts favourably with other applied nutrients and improves their agronomic performance and efficiency in terms of yield response (Rao *et al*., 2017). Silicon is deposited beneath the cuticle as cuticle-silicon double layer in the form of silicic acid. Silica strengthens the plant, protects the plants against insect pests, increases crop production and quality, increases plant nutrition and neutralizes heavy metal toxicity in acid soils. Highly weathered soils are low in available silicon mainly due to leaching loss.

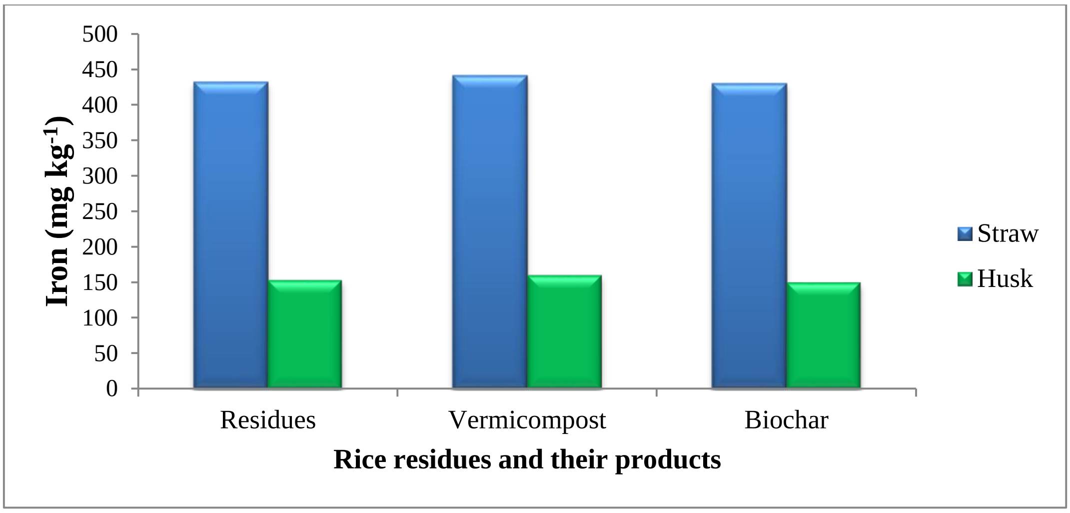


Fig.5.13: Iron content in rice residues and their products

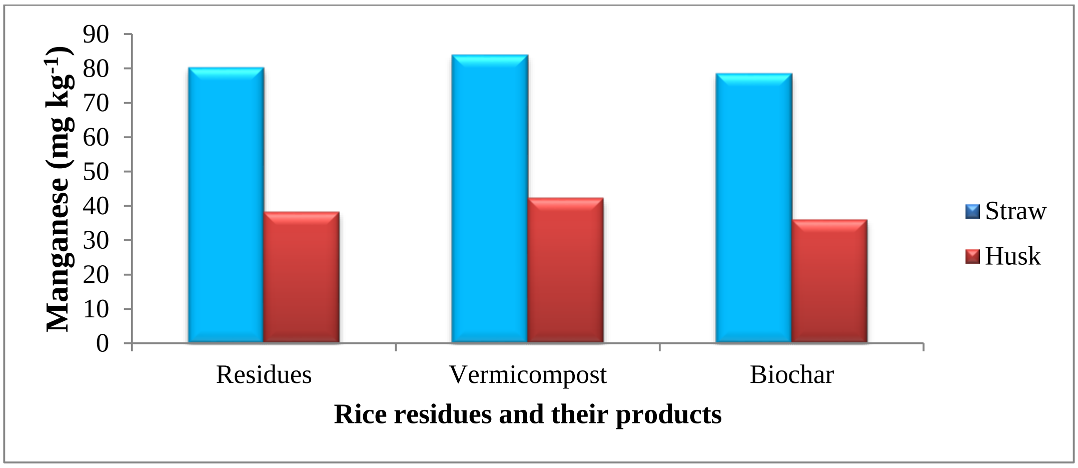


Fig.5.14: Manganese content in rice residues and their products

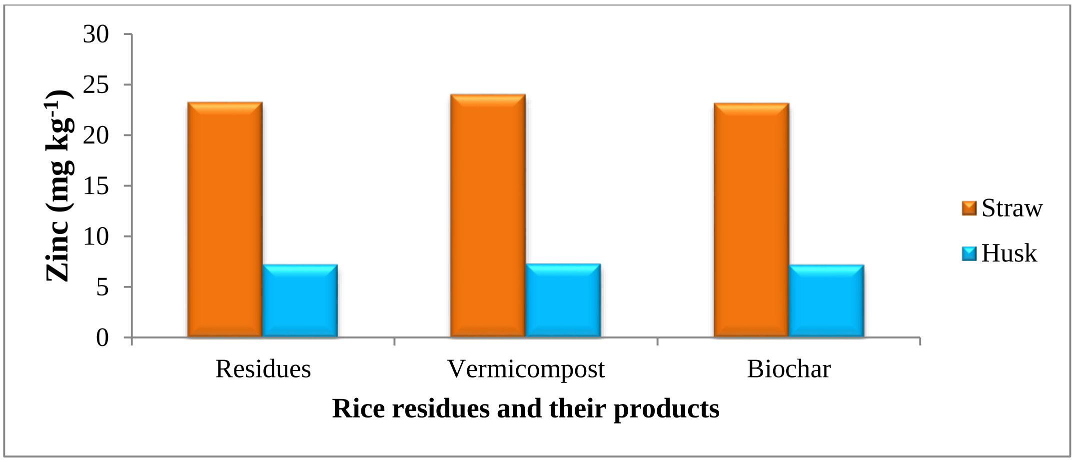


Fig.5.15: Zinc content in rice residues and their products

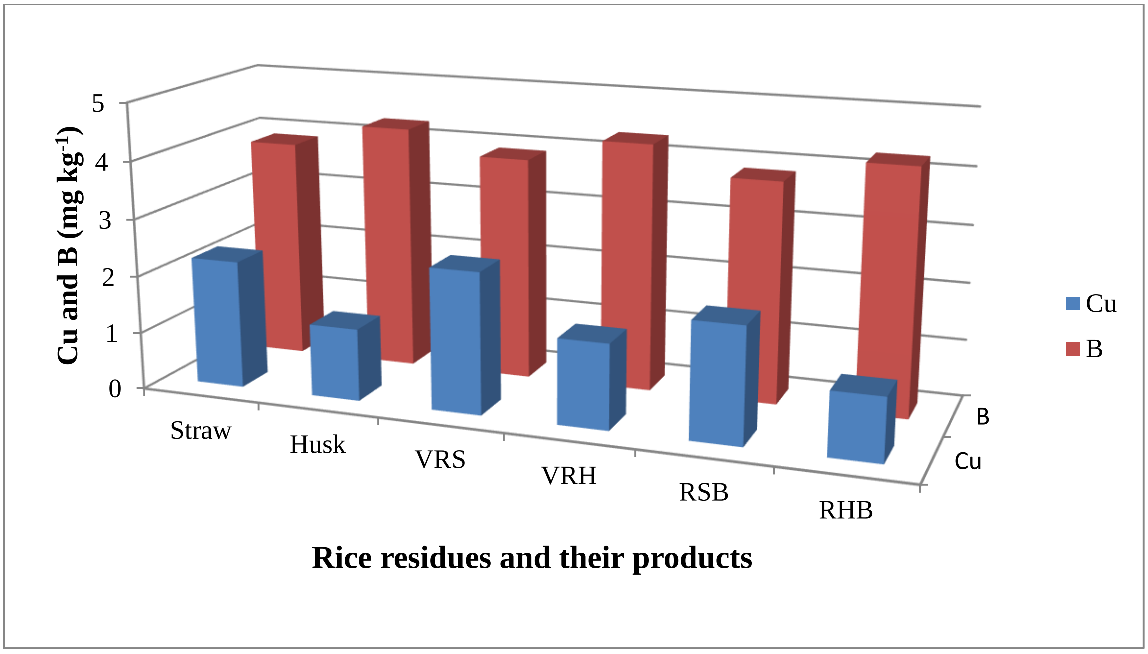


Fig.5.16: Copper and boron content in rice residues and their products

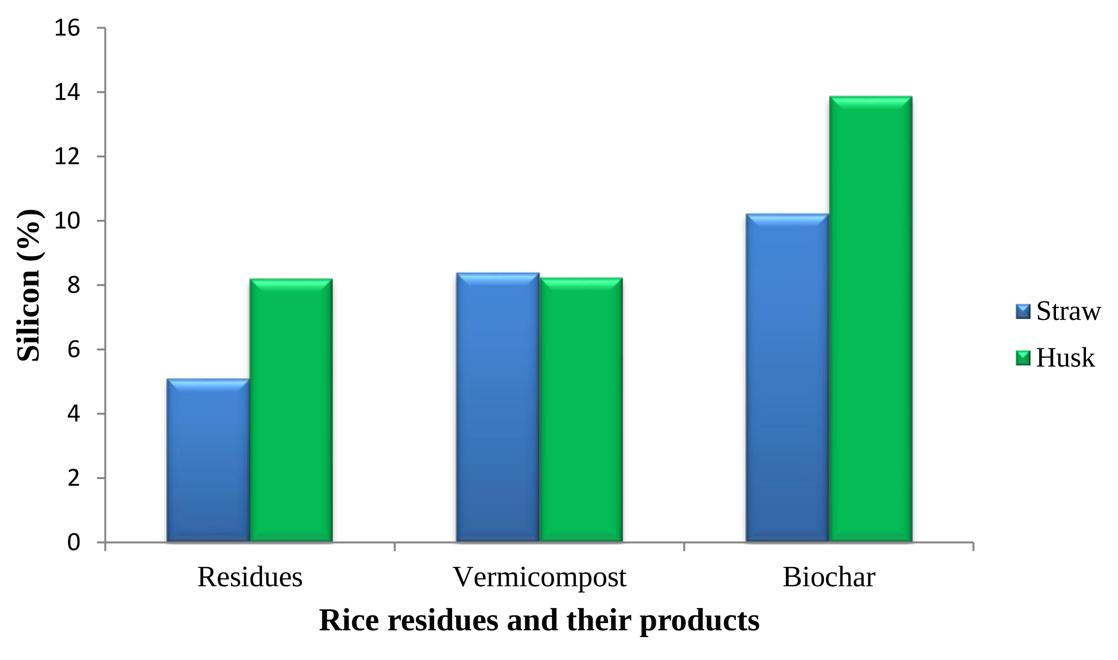


Fig.5.17: Silicon content in rice residues and their products

Its supply is essential for healthy growth and economic yield of the rice crop. Also it improves the tolerance of rice plants to abiotic and biotic stresses. Hence, silicon management is essential for increasing and sustaining rice productivity.

Rice residues contain high quantity of silicon. Among the residues, the husk recorded a slightly higher value for silicon. No other plant part except paddy husk is capable of retaining such a large proportion of silica in it. A combined study using back scattered electron and X-ray images of the husk showed that the silica is distributed mostly under the outer surface of husk (Bui *et al*., 2005). This confirms the general concept of a soluble form of silica getting transported through the plant and concentrating on the outer surface of straw and husk through evaporation.

Vermicomposting and charring of rice residues enhanced the silicon content (Figure 5.17). The decomposition (biological and thermal decomposition during vermicomposting and charring, respectively) of residues as well as its composition resulted in an increase in the nutrient content of final products. Compared to vermicomposting, charring has a great influence on the release of silicon. Xiao *et al*. (2014) reported that pyrolysis temperature caused the intense cracking of carbon components, and thus the silicon located in the inside tissue was exposed to cause enhancement of silicon content in the final product “biochar”.

Cellulose and lignin

The rice husk contained 40.36 per cent cellulose and 27.82 per cent lignin (Figure 5.18-5.19). Hwang and Chandra (1997) reported that the chemical composition of rice husk was similar to that of many common organic fibers with 40-50 per cent cellulose and 25-30 per cent lignin. The cellulose and lignin content of straw was 38.10 per cent 13.26 per cent, respectively. Thygesen *et al*. (2003) reported that straw is a ligno-cellulosic biomass with a cellulose content of 35-40 per cent and lignin content of 10-15 per cent.

The analytical data showed that the content of lignin and cellulose decreased after vermicomposting and charring. The results are in good agreement with the findings of Zhang *et al*. (2015), who reported that thermal degradation of cellulose and lignin occurs under high temperature during biochar production process. The extent of reduction in cellulose was 67.82 per cent in VRS and 48.36 per cent in VRH. The lowest per cent reduction of cellulose in VRH might be due to the incomplete decomposition and high C: N ratio of rice husk.

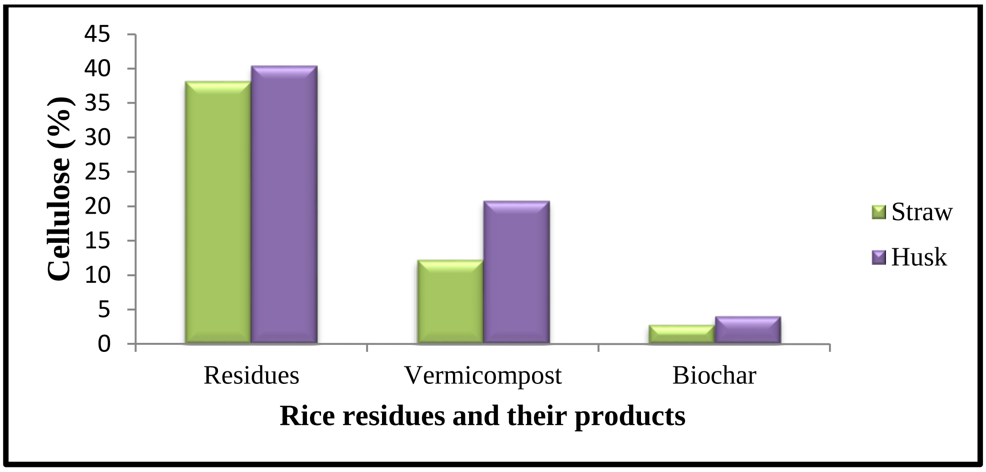


Fig. 5.18: Cellulose content of rice residues and their products

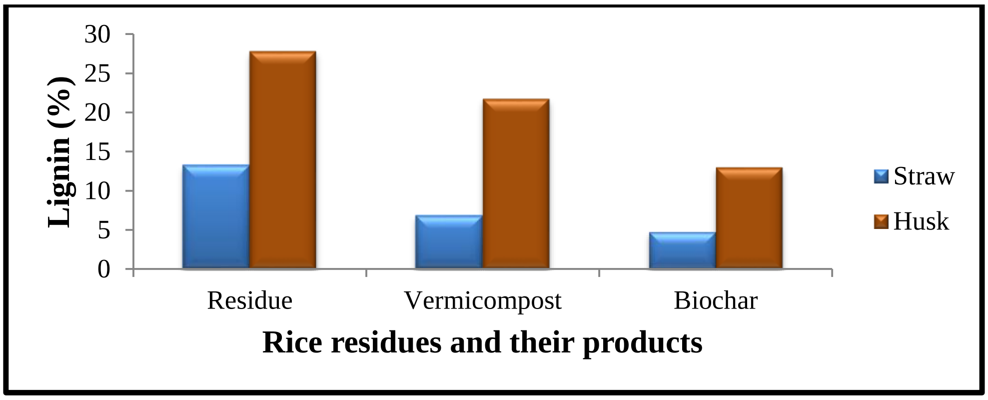


Fig.5.19: Lignin content of rice residues and their products

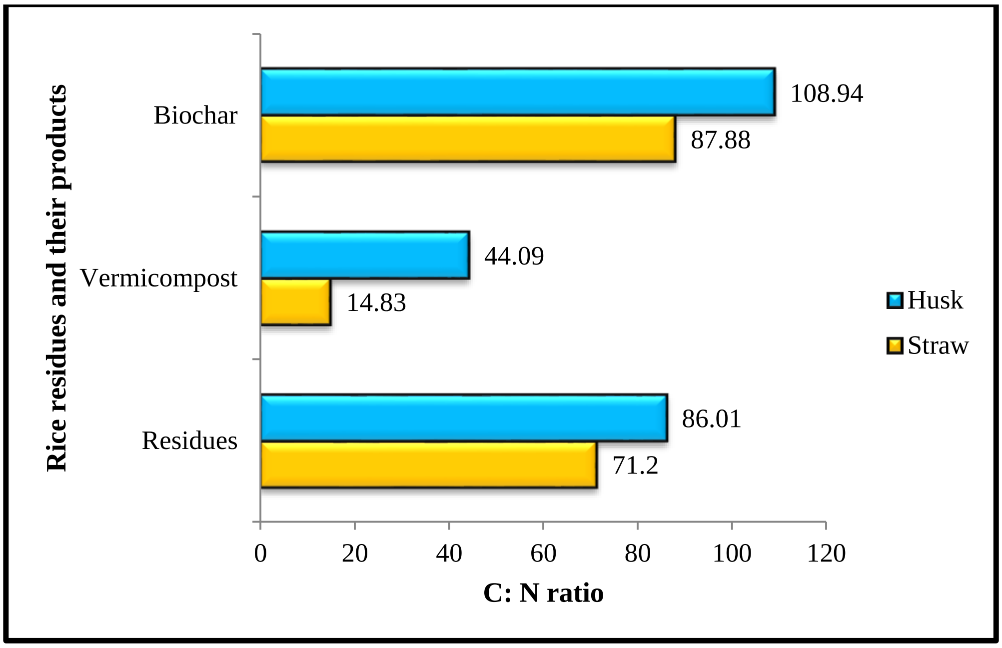


Fig.5.20: C: N ratio of rice residues and their products

Compared to the vermicomposts, the per cent reduction of cellulose was high after charring (92.62 % reduction in RSB and 89.94 % reduction in RHB). The extent of reduction in lignin was lower compared to cellulose in both vermicompost (48.42 % reduction in VRS and 21.82 % reduction in VRH) and biochar (64.25 % reduction in RSB and 53.05 % reduction in RHB). Lignin is a relative complex compound having a cross-linked phenolic-type structure which does not easily breakdown. Due to its aromatic structure, it is more chemically stable and heat resistant than cellulose.

C: N ratio

Ratio of C to N is an index of decomposition and microbial mineralization of residues the optimum being 24:1. Among the rice residues, husk had higher C: N ratio than straw (Figure 5.20).

The substrates with narrow C: N ratio can easily be attacked by microbes and hence mineralized immediately to release the nutrients. Carbon to nitrogen ratio serves as a reliable parameter for the maturity of compost. A remarkable change in the C: N ratio was noticed during the composting of straw and husk. The C: N ratio of VRS and VRH were 14.83 and 44.09 respectively.

The improvement in nitrogen and lowering of carbon resulted in the lowering of the C: N ratio, which is an important criterion for a compost to be fully mature. The results are in good agreement with the findings of Thiyageshwari *et al*. (2018). Singh *et al*. (2014) reported that due to loss of carbon as CO_2, N content of the vermicompost increases causing a decrease in C: N ratio. The C: N ratio was highest in VRH than VRS, and this might be due to the incomplete decomposition of husk on vermicomposting because of high lignin content.

The C: N ratio of biochar was higher than the vermicompost and initial raw materials. The decrease in nitrogen content and condensation of carbon by pyrolysis process might be the reason for high C: N ratio.

5.1.5. Surface morphology

The SEM micrographs of straw and husk exhibited a complex morphology with cell wall composition. The results are in accordance with the findings of Li *et al*. (2012); Arora and Kaur (2018); Chen *et al*. (2017); and Thiyageshwari *et al*. (2018).

SEM analysis of vermicomposted rice straw and husk was carried out to understand the changes in physical structure during vermicomposting. SEM images of vermicomposted straw and husk exhibited porous and disaggregated structure. This might be due to the activity of earthworms during vermicomposting. In the micrograph of vermicomposted rice husk, part of initial rice husk structure containing epidermis was visible. This might be due to incomplete decomposition of husk during vermicomposting because of high lignin content and C: N ratio. In general, SEM image of vermicompost exhibited a highly fragmented and scattered structure contrary to the residues. Results of SEM analysis corroborate with the earlier studies which also reported change in initial substrate morphology after vermicomposting (Kumar *et al*., 2014).

The SEM analysis showed that the structure of biochar was porous, fragmented and heterogeneous. This might be due to the release of volatile compounds released during the pyrolysis process. Similar findings were also reported by Phuong *et al*. (2015).

5.1.6. Structural chemistry

The structure of straw and husk was analysed using FT-IR. Each peak in FT-IR is assigned with corresponding functional groups. The functional group of cellulose, hemicellulose and lignin could be seen in the spectrum. The more number of peaks in FT-IR spectrum of straw revealed its high carbon content than husk. The missing peaks confirm the complete degradation of that compound. In FT-IR spectrum, presence of silicon is illustrated by Si-O-Si and Si-H bond. In the present study such bonds were identifiable in both the residues and their products. Silicon is a major component in chemical structure of rice material, and is typical of its recalcitrant property (Jindo *et al*., 2014).

In general, some differences were detected in the spectrum in terms of intensity of the peak and disappearance of peak after composting and charring. Vermicomposting and charring resulted in the disappearance of some of the ligno-cellulosic bands. Stretching or broadening of peak was mainly due to the chemical alteration during the production process. The increase in transmission percentage reflects the low absorption of infrared light by the functional groups. The percentage transmittance was comparatively lower in products than residues. This might be due to the higher amount of chemical bonds in the product.

The structural chemistry of vermicompost (VRS and VRH) was obtained through FT-IR analysis. In VRS, the O-H stretching of hydroxyl groups from alcohols and carboxylic acid, and N-H stretching vibrations from amides and amines are indicated by a band from 3300-3500 cm^{-1}. Vermicompost had significant level of nitrogen rich compounds and low level of aliphatic or aromatic compounds compared to the raw material or residue, which was confirmed by the FT-IR analysis. The peaks at 2943.75 cm^{-1} and 2896.31 cm^{-1} are assigned to aliphatic methylene groups, found to be decreased in VRS compared to the straw. The reduction in methylene peaks might be due to the decrease in CH_2 and CH_3 groups, which suggested the decomposition of aliphatic compounds after composting. The easily biodegradable compounds decreased after vermicomposting. The aromatic or aliphatic components decreased after composting of straw, while no such difference was noticed in the spectrum of VRH and this might be due to the incomplete decomposition of husk. The presence or absence of spectral peaks for functional groups indicated the stabilization or degradation of residue during bioconversion process (Mayadevi, 2016).

Compared to the FT-IR spectrum of straw and husk, characteristic differences were observed in the spectra of RSB and RHB. The complete disappearance of O-H/N-H stretching (>3000 cm^{-1}) and almost disappearance of aliphatic C-H stretching (3000-2500 cm^{-1}) was noted in the spectrum of biochar. While, peaks arising from the aromatic stretching became more apparent. This implies that greater dehydration and increased aromatization occurred during pyrolysis process. Lee *et al.* (2010) reported that charring temperature modifies the functional groups, and thus aliphatic carbon groups decreases but aromatic carbon increases. Pyrolysis process created more recalcitrant character by increasing aromatic compounds, and is thus suitable for carbon sequestration. The peaks at 1047.15 cm^{-1} (RSB) and 1069.93 cm^{-1} (RHB) clearly observed in the infra-red spectra might be due to the high silica content of biochar. The role of silica is to form molecular bonds with carbon, and are not easily broken at the gasification temperature was earlier reported by Shackley *et al.* (2011), indicating thus the recalcitrant nature of biochar. With RHB and RSB, the bands assigned to the O-H/N-H stretching vibration and the aliphatic C-H stretching vibration almost disappeared, while aromatic carbon bond increased and resulting in high C: N ratio of biochar. Aromatic C=C peaks are an indication of benzene like rings, that have extra stability in the soil (Abdulrazzaq *et al.*, 2014).

5.2. INCUBATION EXPERIMENT

5.2.1. Carbon mineralization and mineralization kinetics

The amount of CO_2–C mineralized during incubation was found to increase with increasing temperature in all the treatments. The results are in agreement with the findings of Xu *et al*. (2010). Soils treated with both organic (S_2, S_3, S_4, S_5, S_6, S_7 and S_8 at T_1, T_2, T_3, and T_4) and inorganic materials (S_9 at T_1, T_2, T_3, and T_4) released significantly more CO_2 –C than the absolute control (S_1 at T_1, T_2, T_3, and T_4). This may be due to the presence of easily degradable carbon in organic materials which enhanced the rate of mineralization. Among the nine treatments, higher mineralizable carbon was found in soils treated with vermicomposted rice straw and this might be due to the presence of relatively higher labile carbon in vermicomposted rice straw than in other input materials as evidenced from the fractionation of carbon in the present study. The carbon mineralization was lowest in biochar (RHB and RSB) added soils than vermicompost (VRS and VRH) and FYM. This might be due to the higher C: N ratio and lesser labile carbon in the biochar which is recalcitrant in nature. Among the rice residues, carbon mineralization was lowest in rice husk treated soils than straw and this might be due to the higher C: N ratio of husk coupled with its high lignin content that reduced the rate of decomposition. The higher CO_2 -C in the soil test based nutrient recommended soils than absolute control can be attributed to the hydrolysis of added urea to NH_4^+ and CO_2. The results are in conformity with findings of Sarma *et al*. (2017).

Decomposition rate and activation energy provide a good insight into the pace of mineralization and decomposability of organic matter in soil. The decrease in decomposition rate observed in all treatments at 45 °C and is possibly due to the exhaustion of substrates for microbial decomposition. At a higher temperature, there may be faster exhaustion of easily available carbon during the initial period of decomposition leaving recalcitrant carbon for later stages, resulting in lower rates of decomposition during the final phases of the incubation experiment. The results are in line with the findings of Fang *et al*. (2005). Sulaiman (2017) also reported a decrease in rate of reaction with increase in temperature in thermal stability studies conducted at different temperatures in the soils collected from permanent manurial plots (started in 1972) in vogue at Regional Agricultural Research station, Pattambi.

Activation energy, that is required to activate atoms or molecules to a condition which helps them undergo chemical transformation or physical transport, indicates the thermal stability of the reactants. The more the activation energy, more is the thermal stability. Application of organic amendments increased activation energy than the mineral fertilizer treated soils. Similar trends were also reported by Sulaiman (2017). The results are also in conformity with the findings of Sandeep *et al.* (2016) wherein it was observed that application of 100 per cent organics were more effective in enhancing the activation energy of SOC than mineral fertilizers. The highest activation energy was found in rice husk biochar amended soil (12.79 kJ mol^{-1}) followed by rice straw biochar amended soil (12.71 kJ mol^{-1}) indicating the thermal stability of recalcitrant carbon and is proved by FT-IR results.

Q_{10} values represent the temperature dependency of the reaction. The results showed that all treatments had Q_{10} values less than one indicating the unavailability of substrates for decomposition as well as increase in recalcitrant nature of substrates at higher temperatures. Sulaiman (2017) reported lower Q_{10} values (<1) due to substrate unavailability for microbial activity rather than a temperature independence of the reaction.

5.2.3. Dehydrogenase activity

Dehydrogenases exist in soil as integral part of intact cells and reflect the total range of oxidative activities of the soil micro flora and it is considered as an index for determining the microbial activity in soil. The treatments were applied just before the commencement of incubation and the sampling immediately after application will certainly not reflect its effect on enzyme activity as evidenced from the non-significant difference in enzyme activity before incubation. Hence, no significant difference was observed in dehydrogenase activity before incubation.

Generally, a decrease in rate of dehydrogenase activity was noted after 110 days of incubation in all treatment combinations (Figure 5.21) compared to the values before incubation. This might be due to the absence or decreased availability of easily degradable compounds. Statistically significant variation in dehydrogenase activity was noted among the 36 treatment combinations after the incubation period. Soil treated with vermicomposted rice straw kept at 15 ºC registered the highest value (31.46 µg TPF g^{-1}day^{-1}).

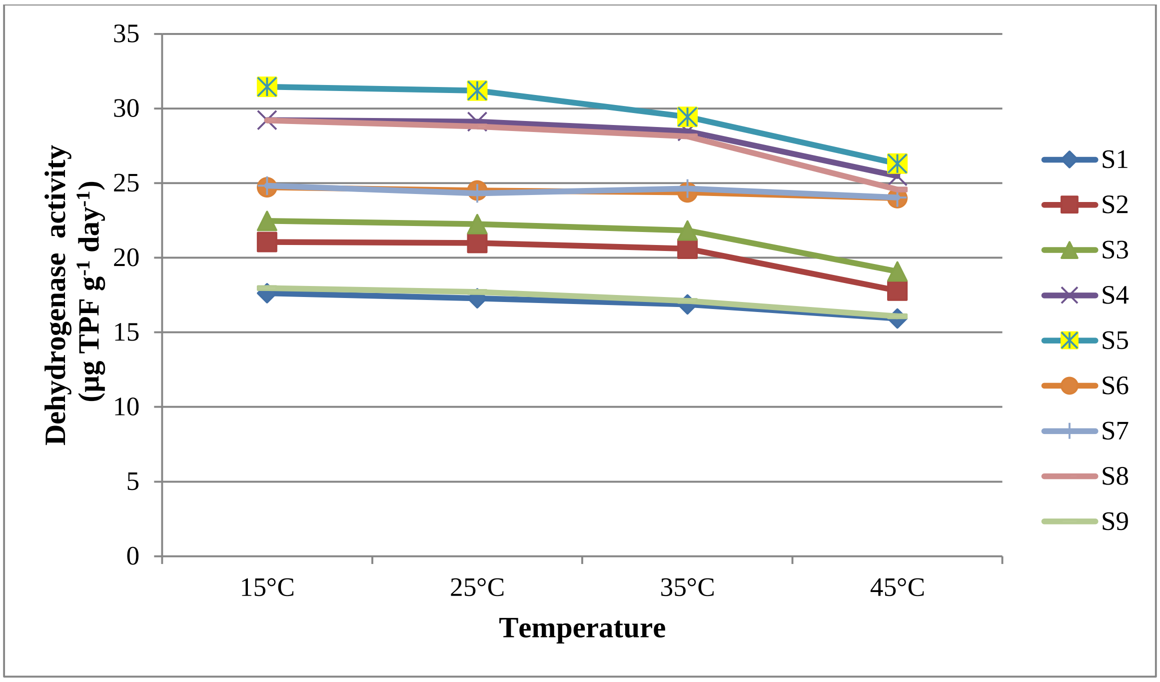


Fig.5.21: Effect of treatments on dehydrogenase activity

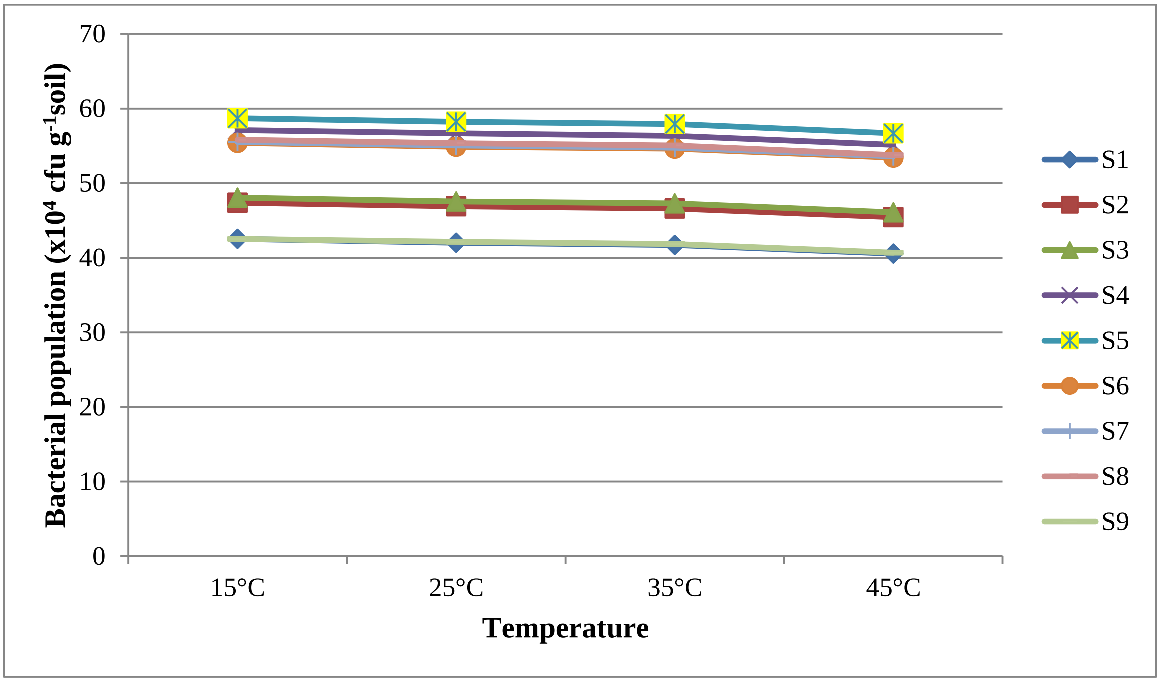


Fig.5.22: Effect of treatments on bacterial population

After 110 days of incubation at four temperatures, dehydrogenase activity was lowest in 45ºC with a mean value of 21.47 µg TPF $g^{-1}day^{-1}$. This might be due to the exhaustion of easily degradable substrates as result of higher temperature that persisted for long. Among the nine treatment sources after incubation period, vermicomposted rice straw treated soils recorded higher dehydrogenase activity with a mean value of 29.60 µg TPF $g^{-1}day^{-1}$. Application of organic amendments significantly enhanced dehydrogenase activity possibly due to utilization of energy in the form of carbon by microorganisms from the organic materials. The higher dehydrogenase activity in FYM and vermicompost than biochar incorporated soil might be due to the presence of easily degradable organic compounds in these amendments. Similar findings were also reported by Sarma *et al*. (2017).

5.2.4. Microbial population

Soil microorganisms play a vital role in decomposing organic matter, cycling of nutrients and fertilising the soil. It also has an important role in developing a healthy soil and sustaining it.

Statistically no significant difference was noted among the treatments in the actinomycetes and fungal population before the commencement of incubation experiment. Bacterial population observed in soil treated with vermicomposted rice straw was significantly superior to that in other treatments. After 110 days of incubation microbial population (bacteria, actinomycetes, and fungi) was found to decrease and this might be due to the reduction in substrate availability.

Bacterial population showed significant variation between the different temperatures (15, 25, 35, and 45 ºC) after 110 days of incubation period with highest at 15 ºC with a mean value of 51.45 $x10^6$ cfu g^{-1}soil and lowest at 45 ºC with a mean value of 49.84 $x10^6$ cfu g^{-1}soil (Figure 5.22). Higher temperature for a longer period adversely affected the growth of microbes. Among the different sources of treatments, higher bacterial population was observed in soil treated with vermicomposted rice straw (S_5) with a mean value of 57.87 $x10^6$ cfu g^{-1}soil. Among the 36 treatment combinations, bacterial population was statistically highest in soils treated with vermicomposted rice straw kept at 15, 25, and 35 ºC.

The population of actinomycetes followed a decreasing trend with increase in temperature (Figure 5.23) with lowest mean value in 45 ºC (4.64 $x10^3$ cfu g^{-1}soil) and highest in 15 ºC (6.22 $x10^3$ cfu g^{-1}soil).

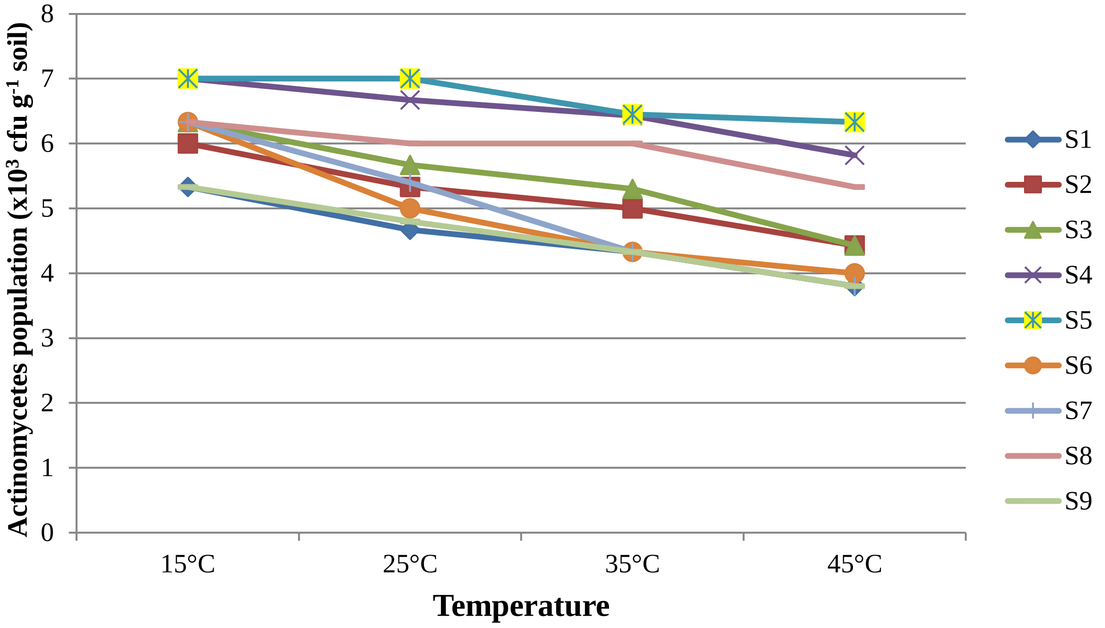


Fig.5.23: Effect of treatments on actinomycetes population

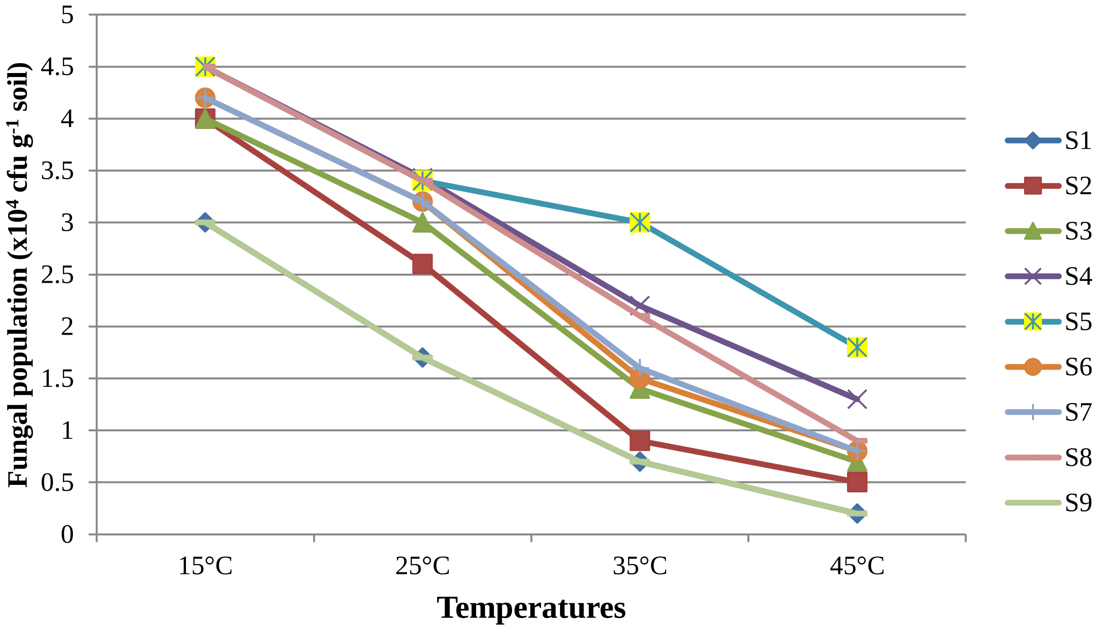


Fig.5.24: Effect of treatments on fungal population

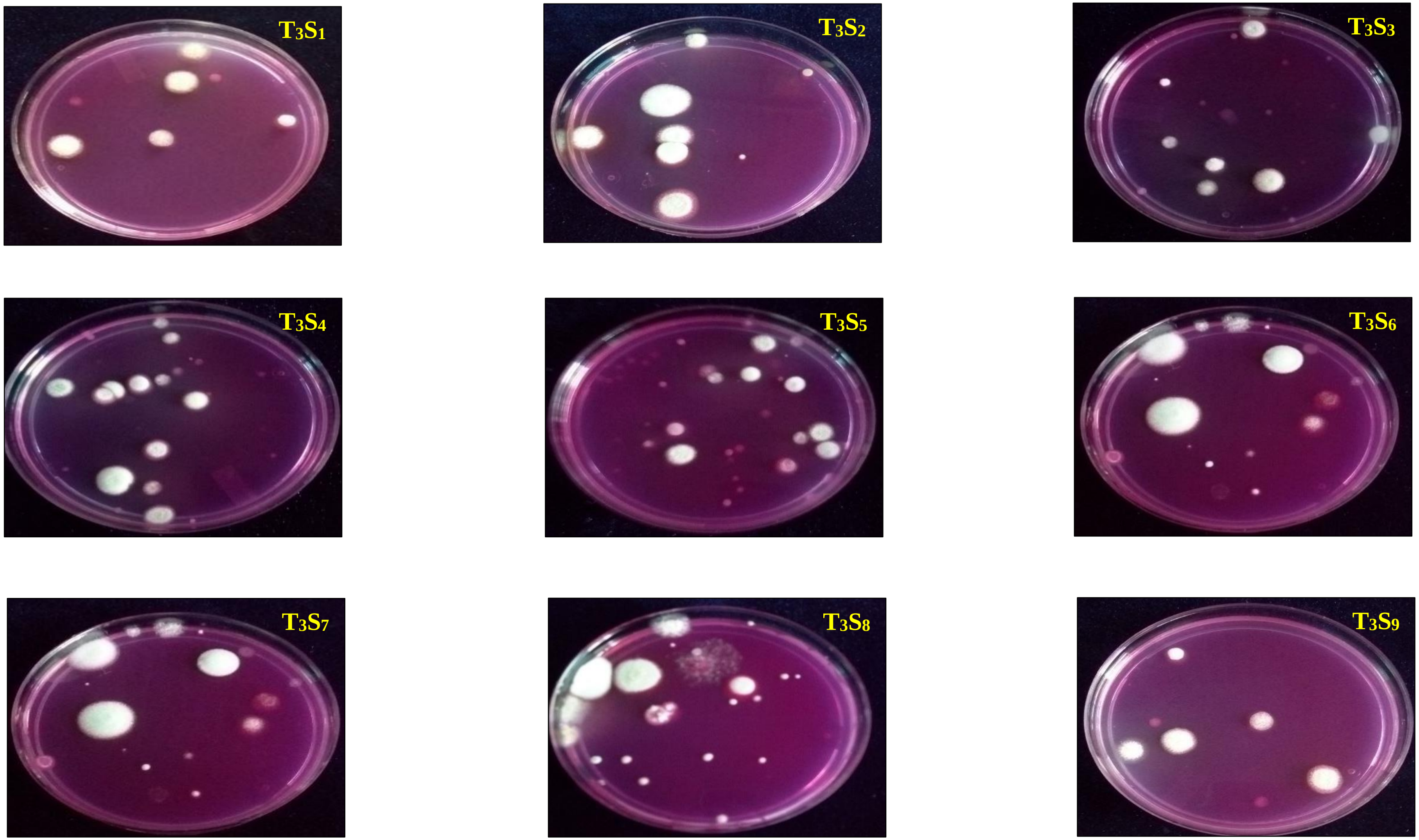


Plate 5.1: Fungal population after 35 ºC incubation period

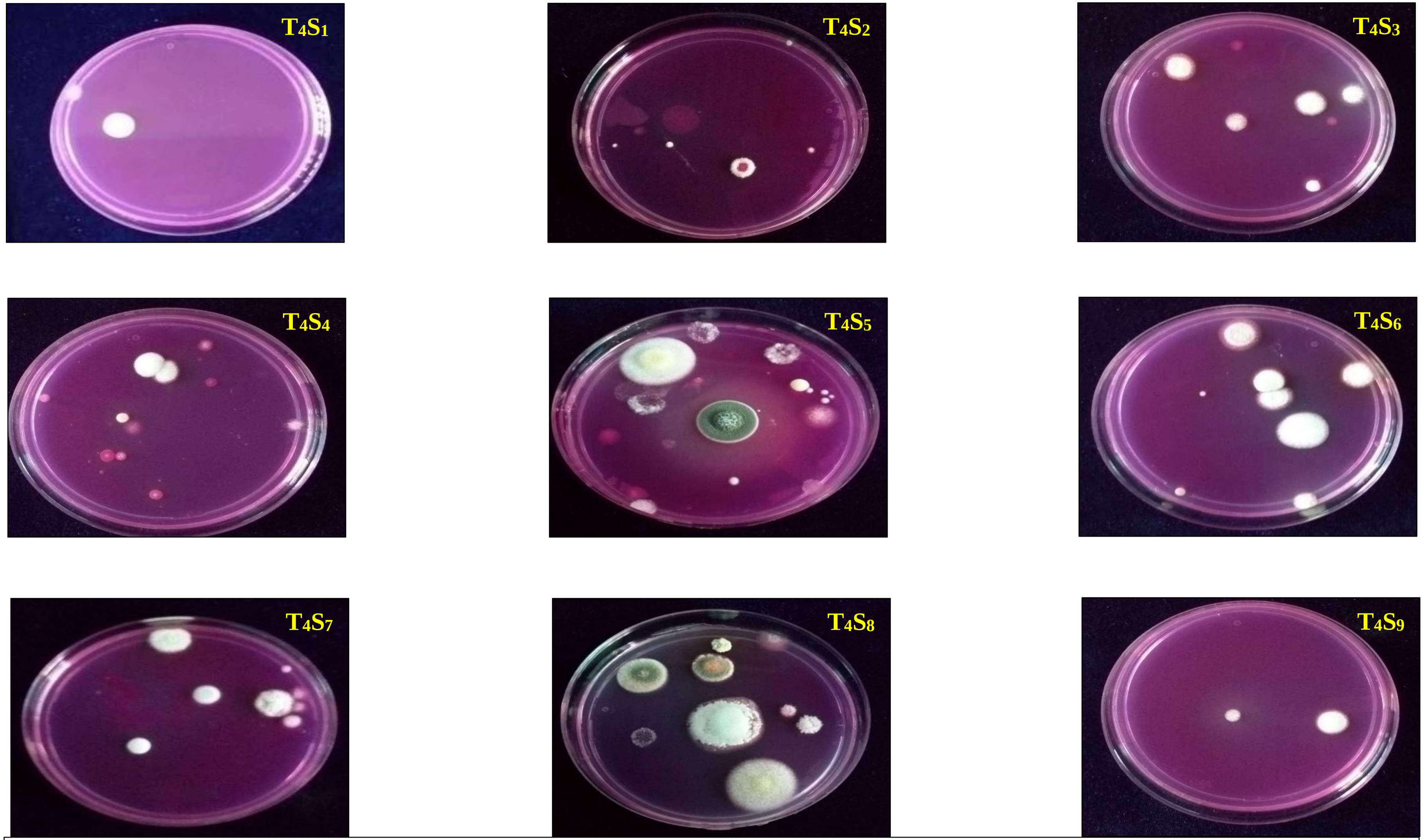


Plate 5.2: Fungal population after 45 ºC incubation period

Significant variation in actinomycetes population was observed among the different sources of treatments with highest mean value recorded in soil treated with vermicomposted rice straw (6.69 x10^3 cfu g^{-1}soil). Actinomycetes population also showed significant variation among the treatment combinations. The highest population of 7.00 x10^3 cfu g^{-1}soil was observed in T_1S_5 (vermicomposted rice straw treated soil under 15ºC), T_1S_4 (vermicomposted rice husk treated soil under 15ºC), and T_2S_5 (vermicomposted rice straw treated soil under 25ºC).

Fungal population showed significant variation between temperatures *viz*., 15, 25, 35, and 45 ºC with highest population mean (3.99 x10^4 cfu g^{-1}soil) was observed at 15 ºC (Figure 5.24). Drastic reduction in fungal population was noted in those soils kept at 35 ºC (Plate 5.1) and 45 ºC (Plate 5.2) and this might be due to the effect of temperature together with the reduction in substrate availability. Among the nine sources, soils treated with vermicomposted rice straw recorded significantly higher population with a mean 3.18 x10^4 cfu g^{-1}soil. Among the 36 treatment combinations, higher fungal population of 4.50 x10^4 cfu g^{-1}soil was observed in T_1S_4, T_1S_5 and T_1S_8 and it was found to be statistically on par with fungal population in T_1S_6 and T_1S_7 with a population of 4.20 x10^4 cfu g^{-1}soil.

Comparatively, higher microbial population was registered in soils treated with vermicomposted rice straw. Vermicomposted rice straw is a well decomposed and stabilized organic substrate with lower forms of carbon and more nitrogen in a form that are available to microbes. Vermicompost contains higher amounts of growth promoting substances, vitamins, and enzymes. So its application increases the population of bacteria, actinomycetes, and fungi (Aiswarya, 2019).

5.2.5. Carbon fractions

Soil is the largest dynamic reservoir of carbon on earth. Soil organic carbon is a strong indicator of soil health. Conceptualization of various fractions of carbon can be made use of to detect even minute changes in management and regulate degradation. Various fractions of carbon *viz*., water soluble carbon (WSC), hot water extractable carbon (HWEC), microbial biomass carbon (MBC), permanganate oxidizable carbon (POXC), and total carbon (TC) were studied in the present investigation.

Statistically no significant difference could be noticed in the fractions of carbon namely WSC, HWEC, MBC, and POXC before commencement of incubation as sampling was done immediately after applying treatments. Whereas, total carbon varied significantly among the treatments with highest value of 1.16 per cent recorded in soils amended with biochar, which was statistically on par with soils treated with vermicompost (1.14%) and FYM (1.14%).

Water soluble carbon (WSC) is the mobile and labile component of organic matter and is either sorbed on soil or sediment particles or dissolved in interstitial pore water (Tao and Lin, 2000). Water soluble carbon showed an increase after the incubation experiment with significant variation among temperatures, sources, and treatment combinations.

The water soluble carbon was found to be increased with rise in temperature (Figure 5.25) and statistically higher mean value was noted in soils treated at 45ºC (109.36 mgkg^{-1}) and lowest in 15 ºC (94.27 mgkg^{-1}). This might be due to the higher decomposition and mineralisation of materials at higher temperature. Soils treated with vermicomposted rice straw (S_5) exhibited highest WSC with a mean value 116.26mgkg^{-1}. This might be due to the higher decomposition of vermicompost as a result of narrow C: N ratio as evidenced from the characterization of the rice residues and their products in the present study. Among the 36 treatment combinations, highest WSC was obtained in T_4S_5 (133.32mgkg^{-1}).

Hot water extractable carbon constitutes the simple organic compound and microbial biomass which are hydrolysable under the given extraction condition (Weigel *et al*., 2011). Hot water extractable carbon differed significantly among different temperatures, sources and treatment combinations.

Vermicompost treated soil (S_5) registered higher HWEC with a mean value 461.09 mgkg^{-1}. Among the different temperatures studied, soils kept at 45ºC recorded significantly higher HWEC (455.90 mgkg^{-1}) in comparison to soils kept at 15ºC that recorded the lowest (446.67 mgkg^{-1}) (Figure 5.26). Among the treatment combinations, T_4S_5 recorded highest HWEC (466.36mgkg^{-1}).

Microbial biomass carbon (MBC) is a measure of carbon contained in the living component of soil organic matter which consists of bacteria, fungi and contributes to 1-5 per cent of total soil organic carbon. The microbial biomass carbon differed significantly among the different temperatures, sources and treatment combinations.

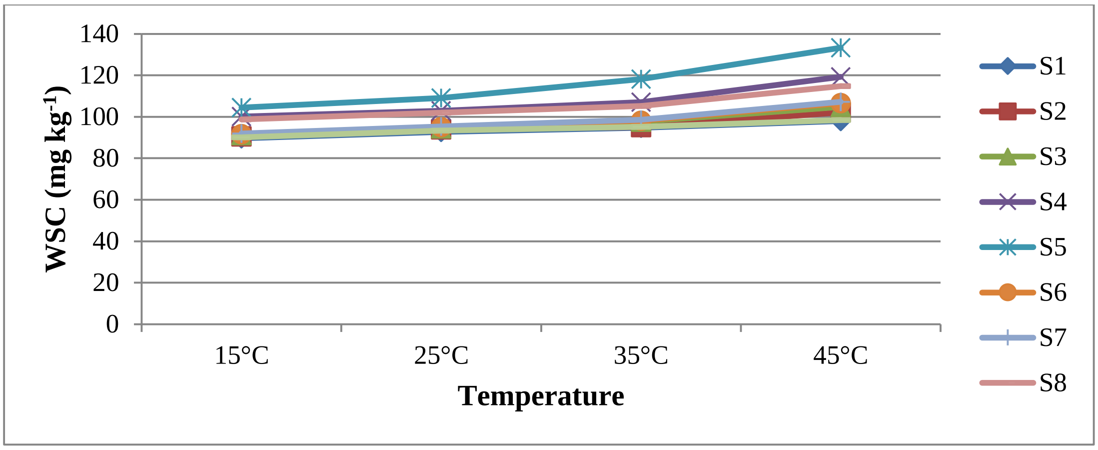


Fig.5.25: Effect of treatments on WSC after incubation at different temperatures

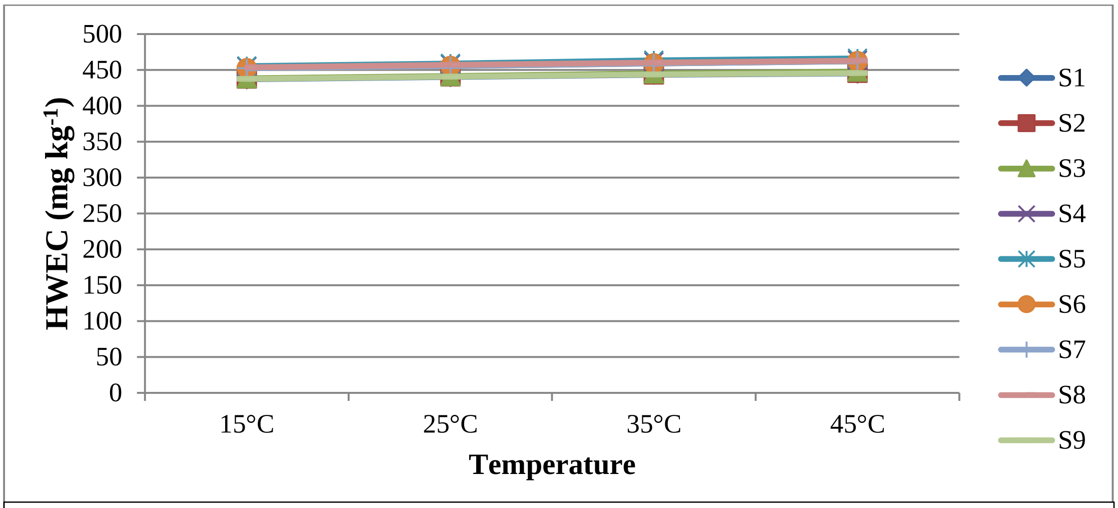


Fig.5.26: Effect of treatments on HWEC after incubation at different temperatures

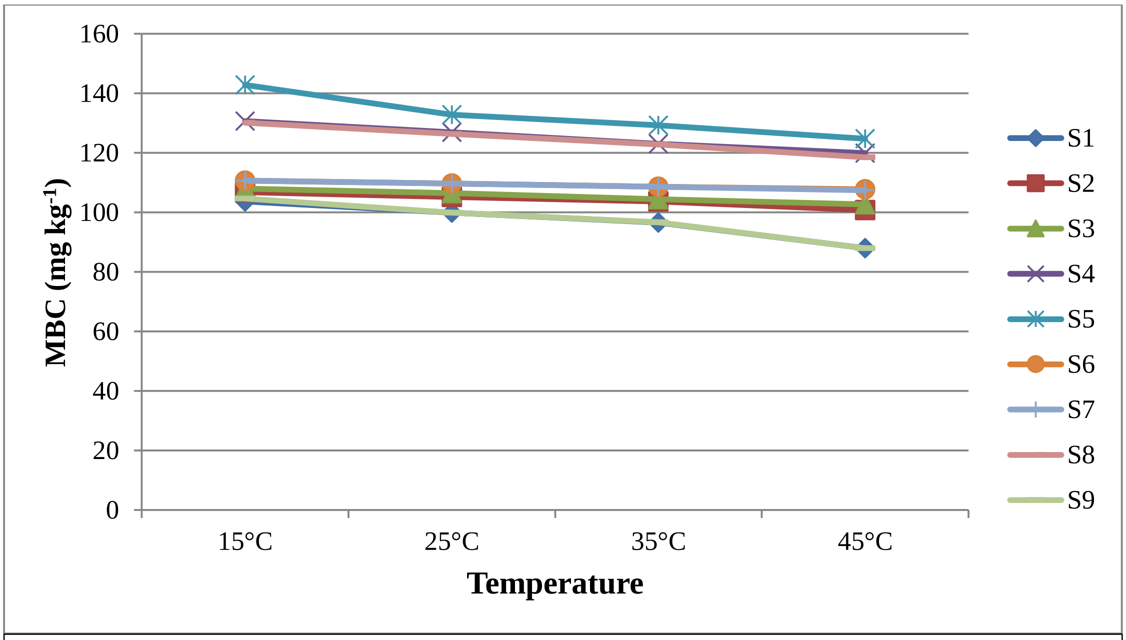


Fig.5.27: Effect of treatments on MBC after incubation at different temperatures

Among the nine sources, soils treated with vermicomposted rice straw recorded highest MBC with a mean value 132.44 mg kg^{-1}. This may be probably due to higher microbial activity in vermicomposted rice straw amended soils.

Temperature had significant effect on MBC. Qi *et al*. (2016) reported that microbial biomass carbon significantly responded to temperature changes and it decreased with increasing temperature (Figure 5.27). They also pointed out that MBC was the most sensitive index for reflecting the change in carbon content. In the present study, highest MBC was found in soils treated at 15 ºC (116.46 mgkg^{-1}) and lowest in 45 ºC with a mean value of 106.44 mg kg^{-1}.The MBC was lowest in soils treated with higher temperature for a long time than the soil kept in lower temperature.

Among the different 36 treatment combinations studied, statistically highest MBC was noted in soil treated with vermicomposted rice straw and kept at 15 ºC (142.80 mg kg^{-1}) and lowest in absolute control at 45 ºC (87.97 mg kg^{-1}), which was on par with soil added with chemical fertilizer kept at 45 ºC (88.01 mg kg^{-1}).

Permanganate oxidisable carbon (POXC) comprises of readily oxidisable components and accounts to 5-30 per cent of soil organic carbon (Blair *et al*., 1995) and is obtained by the chemical oxidation of organic matter by weak potassium permanganate solution. Statistically significant variation was noticeable among the different temperatures, sources and treatment combinations after the incubation period. The highest POXC was recorded in vermicomposted rice straw amended soils (1390.60 mg kg^{-1}).

Permanganate oxidizable carbon differed significantly among the different temperatures (Figure 5.28). The highest POXC was noted in T_1 (1340.80 mg kg^{-1}) and lowest in T_4 (1065.56 mg kg^{-1}). Among the treatment combinations, T_1S_5 registered highest POXC (1426.83 mg kg^{-1}). Andrews *et al*. (2004) reported that the turnover time of POXC is shorter and hence more sensitive to management practices.

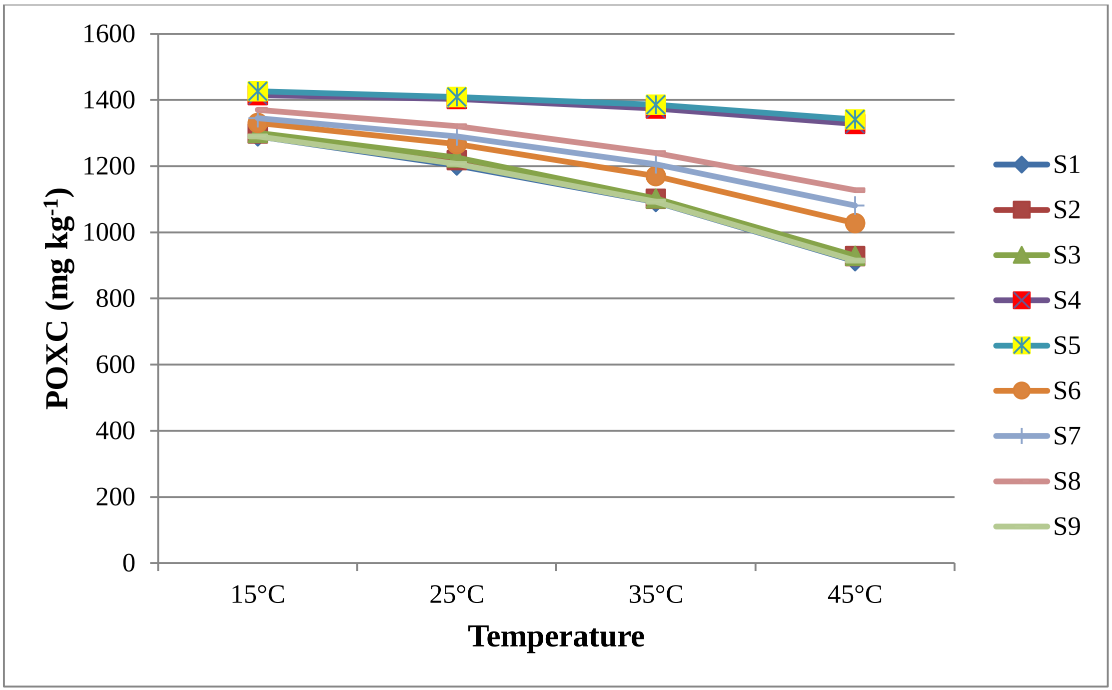


Fig.5.28: Effect of treatments on POXC after incubation at different temperatures

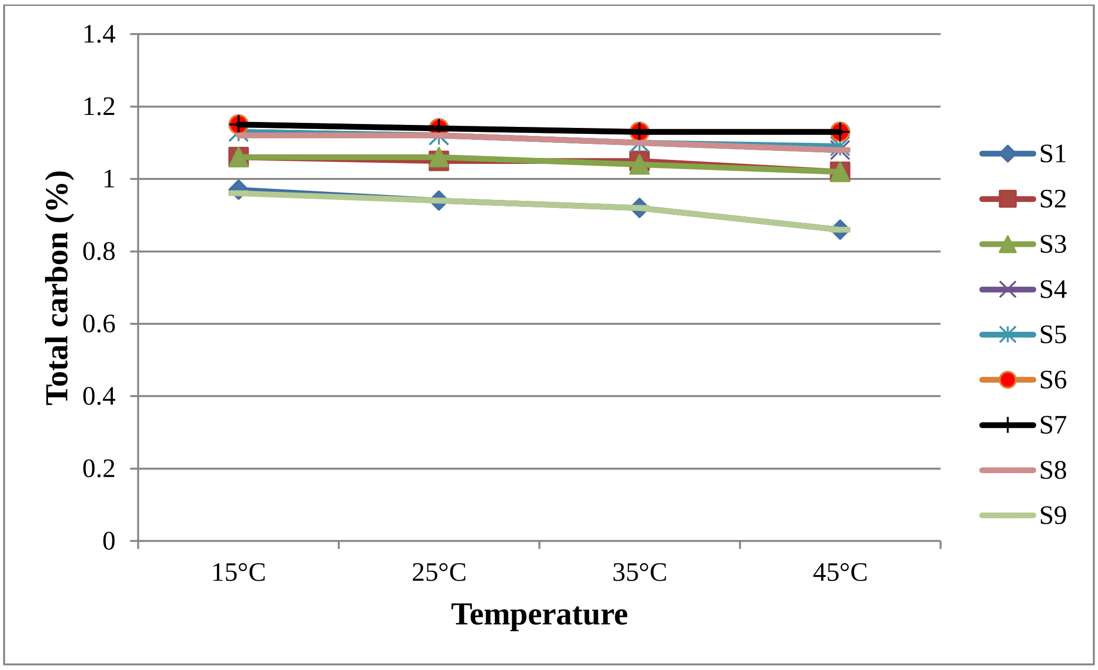


Fig.5.29: Effect of treatments on total carbon after incubation at different temperatures

Total carbon was found decrease after the incubation compared to total carbon before the commencement of incubation. Statistically significant differences were observed among the temperatures, sources and treatment combinations. Total carbon was found to be lowest in soils treated at 45 ºC with a mean value of 1.03 per cent (Figure 5.29).

Higher temperature significantly decreased the total carbon. This might be due to the greater decomposition of materials at higher temperature that resulted in the release of easily available organic materials for microbial consumption, being the sole source of substrates during incubation period. Allison *et al*. (2010) pointed out that warming accelerated the decay of carbon and this might have resulted from the increase in decomposition and mineralization with increasing temperature and efficiency of soil microbes in using organic carbon.

Biochar amended soils (S_6 and S_7) recorded higher total carbon (1.14 %) while the lowest was in absolute control and in soil treated with nutrients (chemical fertilizer) registering a mean value of 0.92 per cent. The higher carbon in biochar amended soils might be due to the presence of recalcitrant carbon contained in it. Among the 36 treatment combinations, significant variation was observed in carbon content with T_4S_1 and T_4S_9 registering the lowest value of 0.92 per cent.

5.3. FIELD EXPERIMENT

5.3.1. Monitoring Eh and pH

5.3.1. 1. Eh

The study of redox potential will help us in better understanding of the rice environment which influences the growth, nutrition, and yield. Oxidation- reduction is a chemical reaction in which electrons are transferred from a donor to an acceptor. The electron donor losses electrons and increase its oxidation number or is oxidised, the acceptor gains electrons and decrease its oxidation number or is reduced. The source of electrons for biological reduction is organic matter. Soils rich in organic matter or readily decomposable residues had a thin oxidized layer (Das, 2010). He also reported that oxidized layer was several centimetre thick in lateritic soils because of its poor organic matter status and high percolation status. Soil disturbances like weeding and other intercultural operations resulted in the oxidised condition and hence an increment of Eh in all the treatments at four weeks of transplanting (Figure 5.30). Further decrease in Eh in all the treatments might be due to the undisturbed condition prevailing in field.

In the present study, absolute control recorded higher Eh compared to all other treatments and this might be due to lower organic matter status in experimental soil. The application of residues and its products had profound influence in lowering redox potential. This might be due to the presence of decomposable organic matter in the residues and its products. However, biochar treated soils along with soil test based nutrients resulted in higher Eh than the soils added with residues and vermicompost along with soil test based nutrients. This might be due to the lower decomposition of added biochar because of its high C: N ratio and highly aromatic and condensed carbon structure as evidenced from the FT-IR data. The results are in agreement with the findings of Chesworth and Redox (2004); Chen *et al*. (2014) and Joseph *et al*. (2015).

5.3.1.2. Soil pH

The change in soil pH that results from the application of any input is worth estimating. The difference in pH brought about by treatment application was studied under field condition (Figure 5.31). The alkaline nature of rice residues and their products resulted in higher pH of experimental soil.

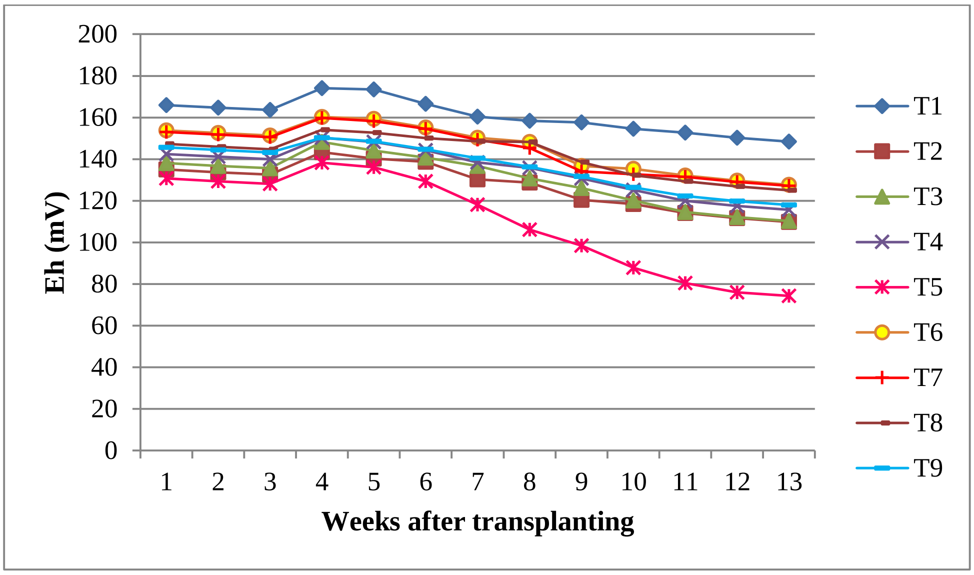


Fig.5.30. Changes in Eh at weekly intervals

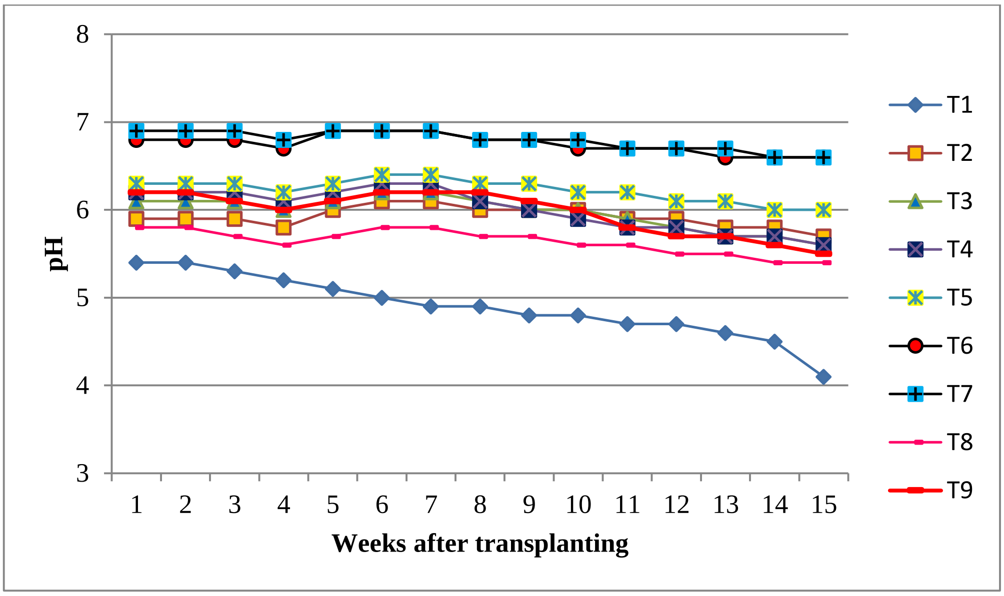


Fig.5.31. Changes in pH at weekly intervals

The soil pH followed a decreasing trend. Whereas, there was a slight increment in soil pH after four weeks of transplanting in all the treatments except T_1. This might be due to the effect of lime. The second split of lime application coincides with the four weeks of transplanting. The increase in soil pH immediately after application of lime was earlier reported by Geetha (2015). The biochar amended treatments showed a higher soil pH at all the weeks studied and this might be due to the alkalinity of biochar as evidenced from the first experiment of the present study. The liming effect and alkaline nature of biochar was earlier reported by Dainy (2015).

5.3.2. Soil characteristics

5.3.2.1. Physical properties

The application of various treatments had profound influence in altering soil physical properties *viz*., lowering soil bulk density, increasing porosity, MWD, and water holding capacity (Figure 5.32-5.35).

Bulk density of the soils was reduced with the application of various treatments except absolute control. Bulk density is of greater importance than particle density in understanding the physical behaviour of soils. Generally, soils having low bulk densities exhibit favourable physical condition. In the present study, the lowest bulk density was observed in biochar treated soil and highest in absolute control. However, porosity was found to be highest in biochar added soil and lowest in absolute control.

The influence of organic residues in reducing soil bulk density and increasing soil total porosity was earlier reported by Mbagwu (1989). They also pointed out that the reduced bulk density and increased porosity controls the water movement and gas exchange in soil and also favoured the soil microorganisms by providing the required water and oxygen. Porosity directly control the amount of water and air in the soil and indirectly influence the plant growth and crop production (Das, 2010).

Mean weight diameter (MWD) is one of the important indices of soil aggregation. Aggregate stability is mainly brought about by the interaction between soil clay and organic matter. Soil aggregation plays an important role in crop production. The degradation of soil can be reduced to a great extent with good aggregation. Soil added with biochar and vermicompost recorded highest MWD and absolute control registering the lowest.

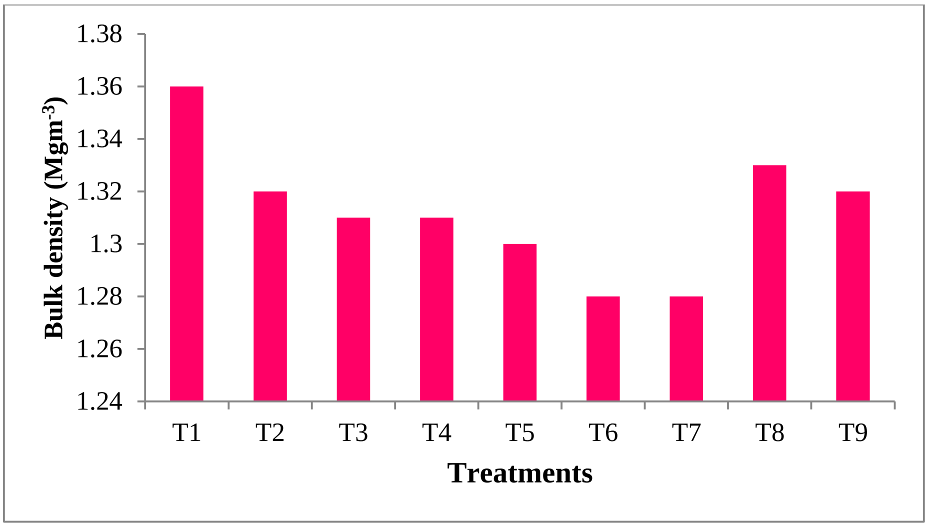


Fig.5.32. Effect of treatments on soil bulk density

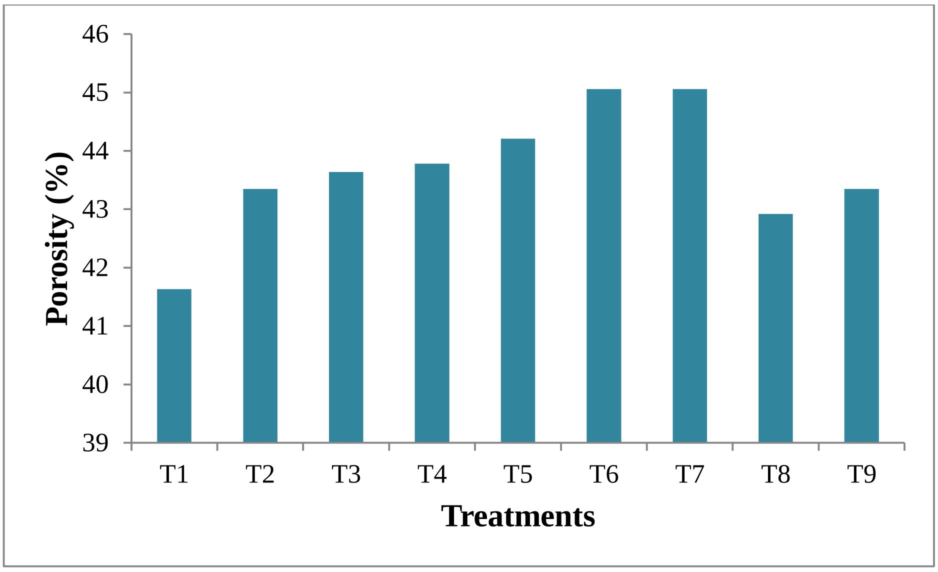


Fig.5.33. Effect of treatments on porosity

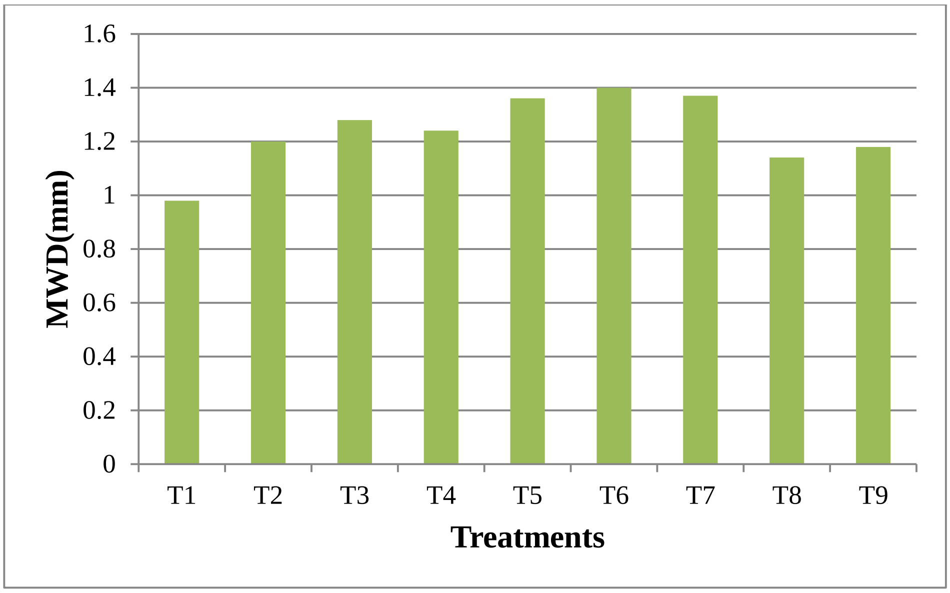


Fig.5.34. Effect of treatments on mean weight diameter (MWD)

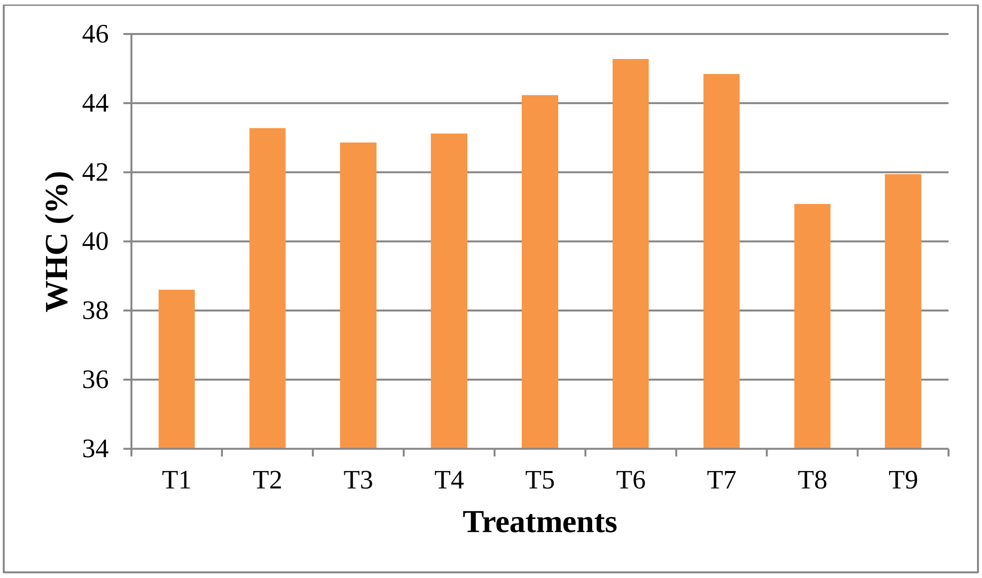


Fig.5.35. Effect of treatments on water holding capacity (WHC)

High water holding capacity would have helped in improving infiltration rate. Soil amended with biochar recorded highest water holding capacity. This might be due to the highly porous nature of biochar.

The application of rice residues and their products in lowering bulk density and increasing porosity, water holding capacity and mean weight diameter were also reported by Nyborg *et al*. (1995); Glaser *et al*. (2002); Gundale and De-Luca, (2006); Herath *et al*. (2013); Ogbe *et al*. (2015) and Persaud *et al*. (2018).

5.3.2.2. Chemical properties

The chemical properties of post-harvest soil are depicted in Figure 5.36-5.48. Soil amended with rice residues and their products such as vermicompost and biochar had an effect in increasing the carbon content of soil. Among the various treatments studied, soil test based nutrient application along with biochar applications (rice straw biochar and rice husk biochar) resulted in an increase in carbon content and it was found to be on par with soil added with soil test based nutrient application and vermicomposted rice straw.

Application of vermicomposted rice straw along with soil test based nutrient recommendation resulted in an increase in nitrogen content of the soil (364.68 kg ha^{-1}). This might be due to the presence of higher nitrogen content in the vermicompost and it was evidenced from present study on characterization.

Higher phosphorus content was noticed in plots that received soil test based nutrient recommendation and vermicomposted rice straw at 5 t ha^{-1} (24.86 kg ha^{-1}). Higher phosphorus content in vermicompost than the rice residues and biochar resulted in the increased phosphorus status of experimental soil.

Significant increase in potassium content was observed after the combined application of soil test based nutrient recommendation and rice straw biochar at 5 t ha^{-1} (326.23 kg ha^{-1}). This might be due to the higher potassium contained in rice straw biochar as indicated in the characterization experiment.

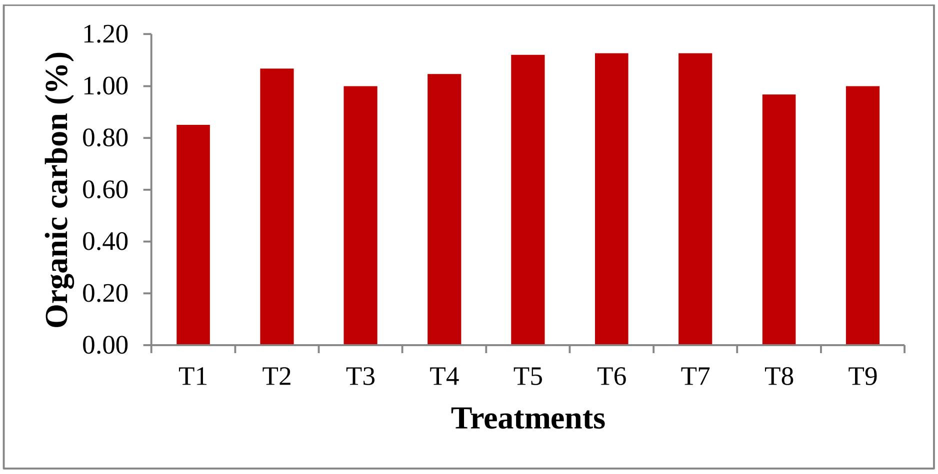


Fig.5.36: Effect of treatments on organic carbon content in post- harvest soil

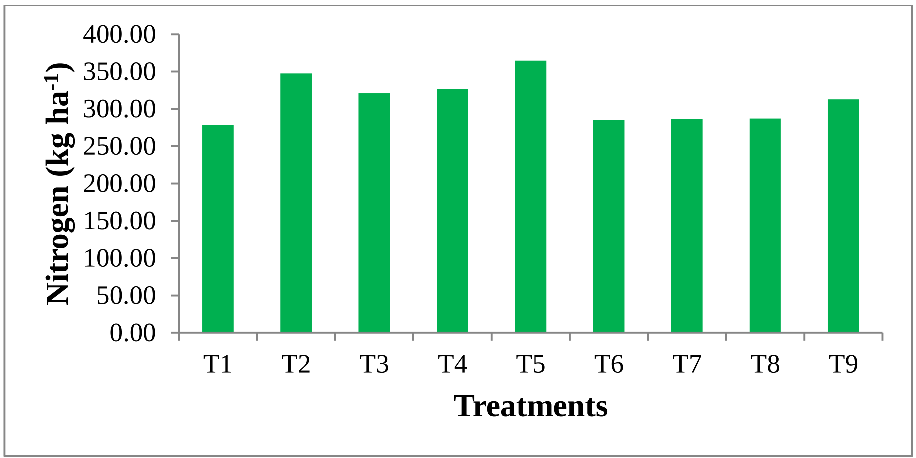


Fig.5.37: Effect of treatments on nitrogen content in post- harvest soil

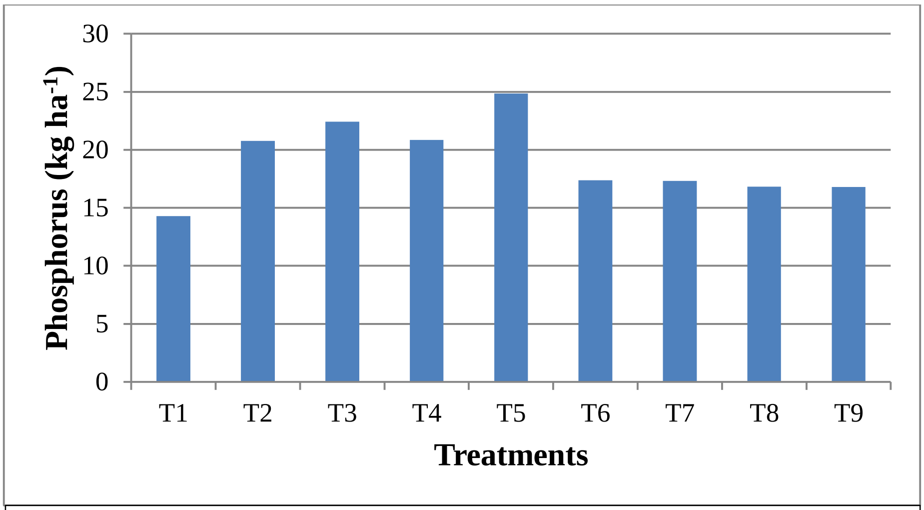


Fig.5.38: Effect of treatments on phosphorus content in post- harvest soil

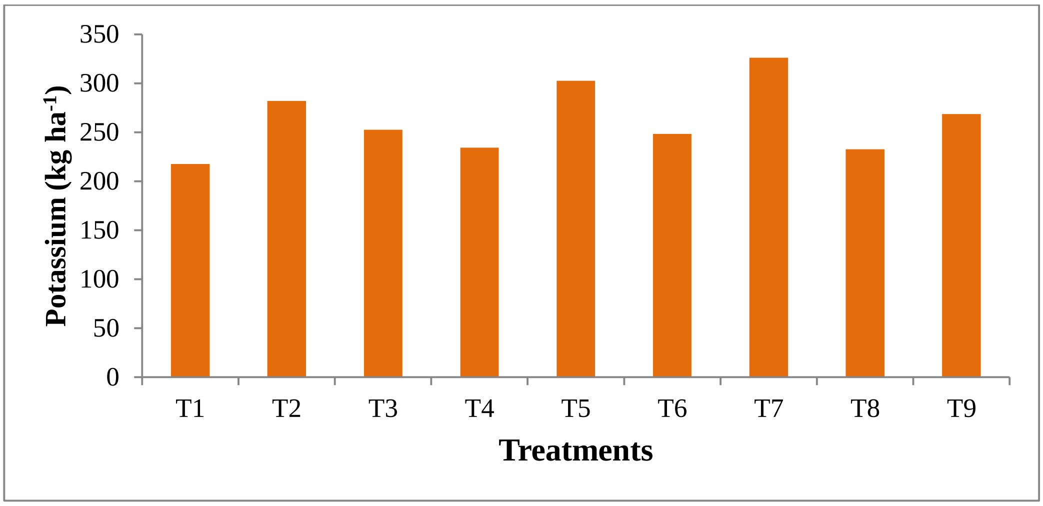


Fig.5.39: Effect of treatments on potassium content in post- harvest soil

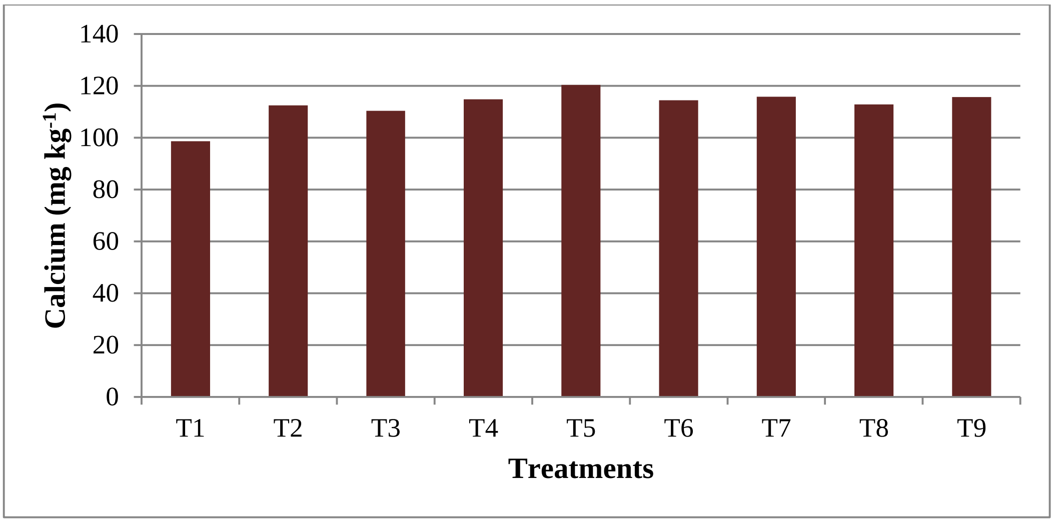


Fig.5.40: Effect of treatments on calcium content in post- harvest soil

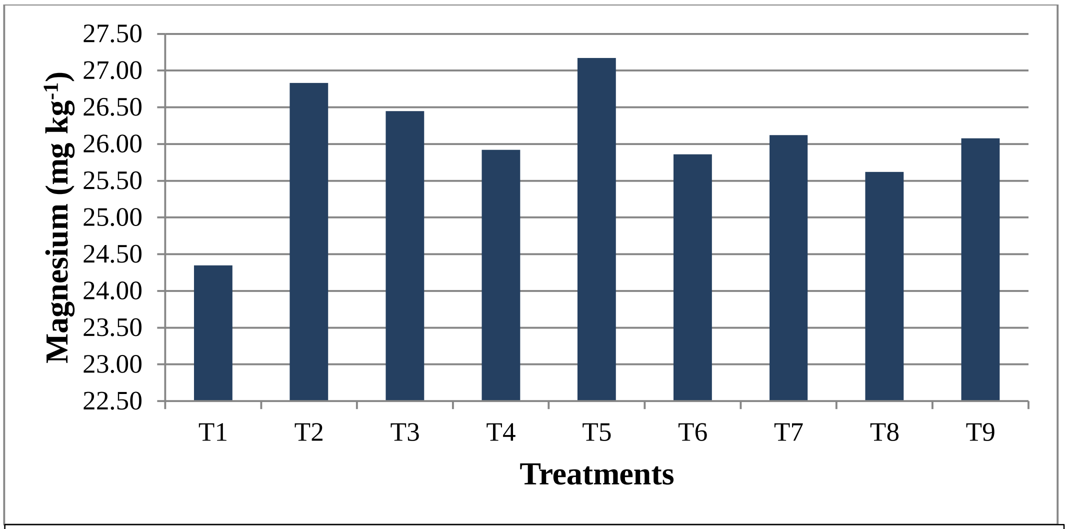


Fig.5.41: Effect of treatments on magnesium content in post- harvest soil

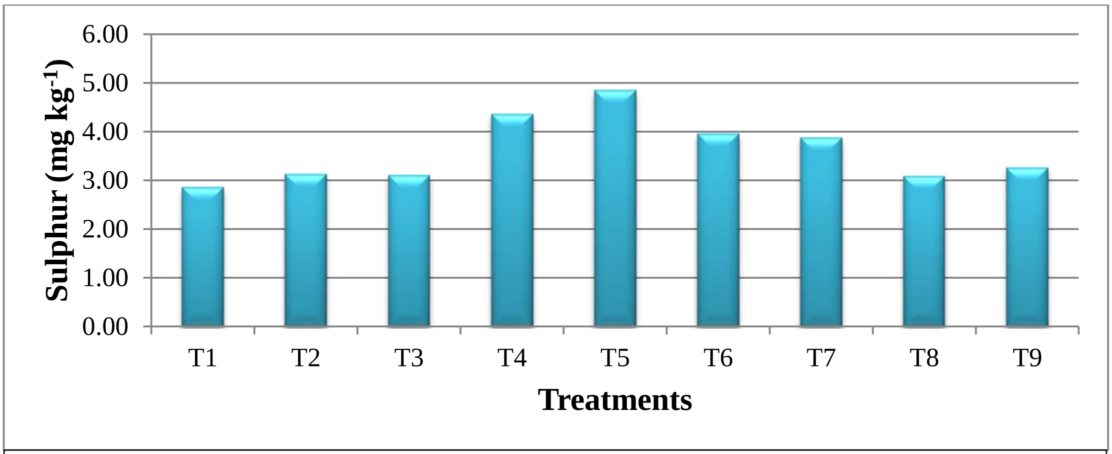


Fig.5.42: Effect of treatments on sulphur content in post- harvest soil

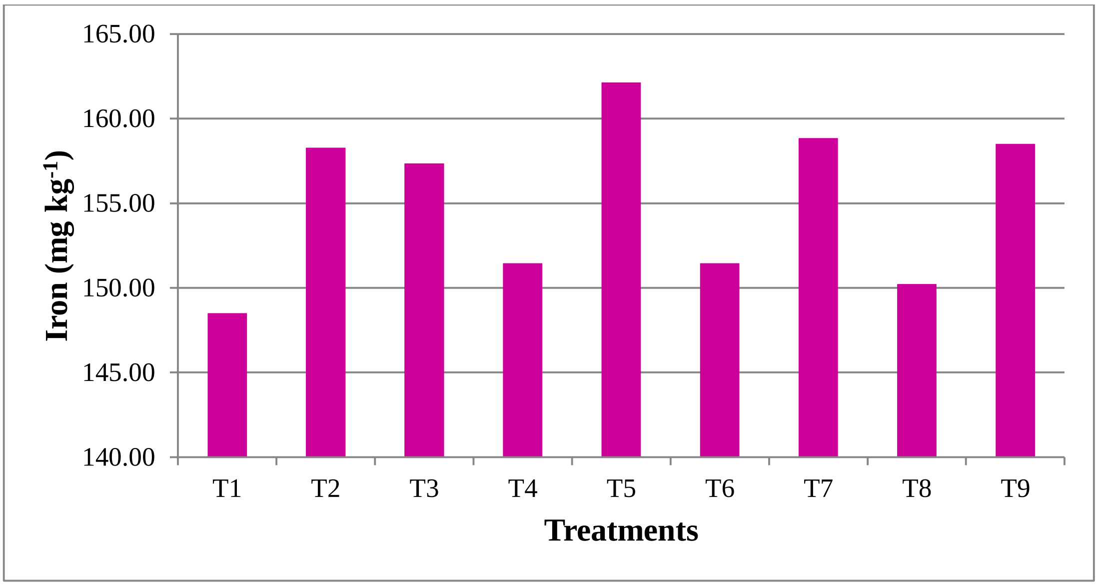


Fig.5.43: Effect of treatments on iron content in post- harvest soil

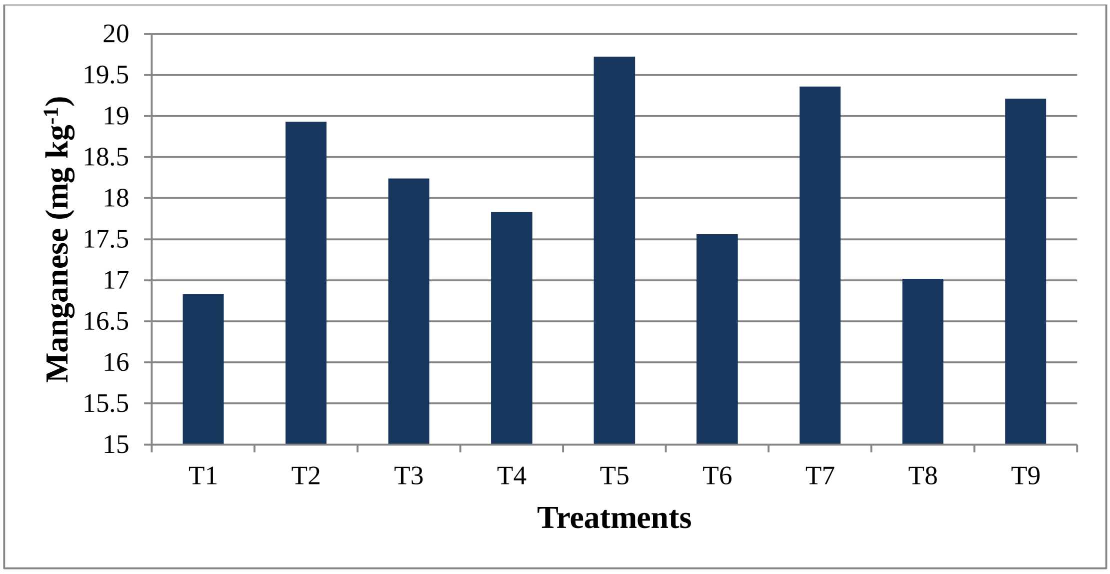


Fig.5.44: Effect of treatments on manganese content in post- harvest soil

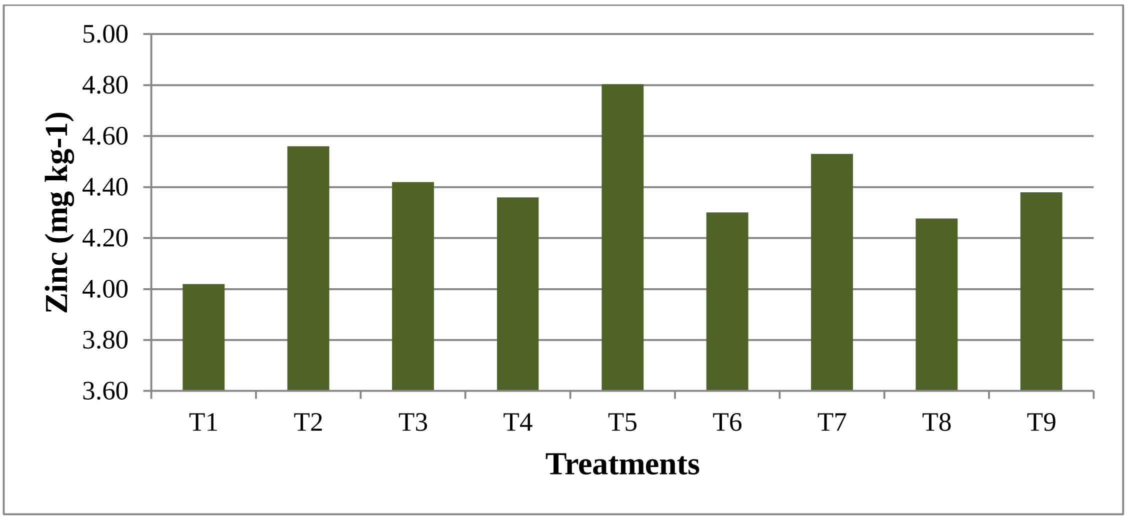


Fig.5.45: Effect of treatments on zinc content in post- harvest soil

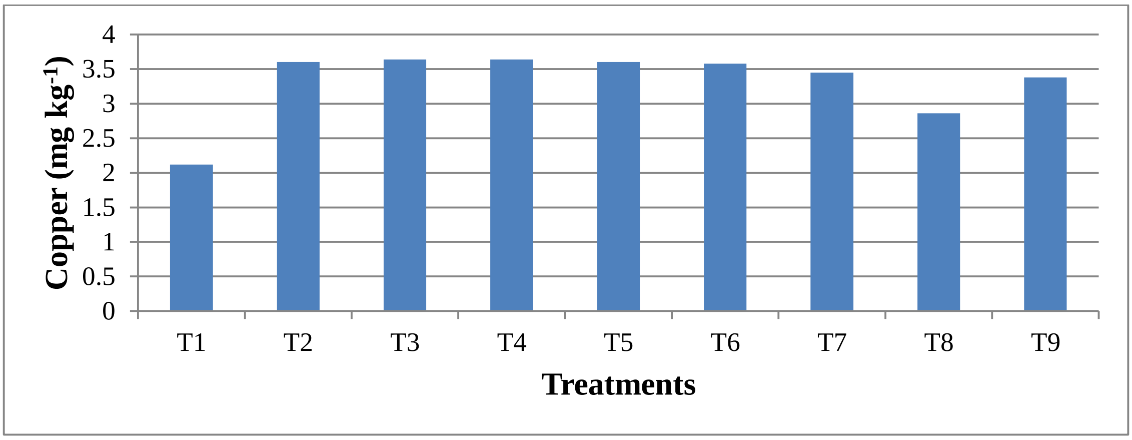


Fig.5.46: Effect of treatments on copper content in post- harvest soil

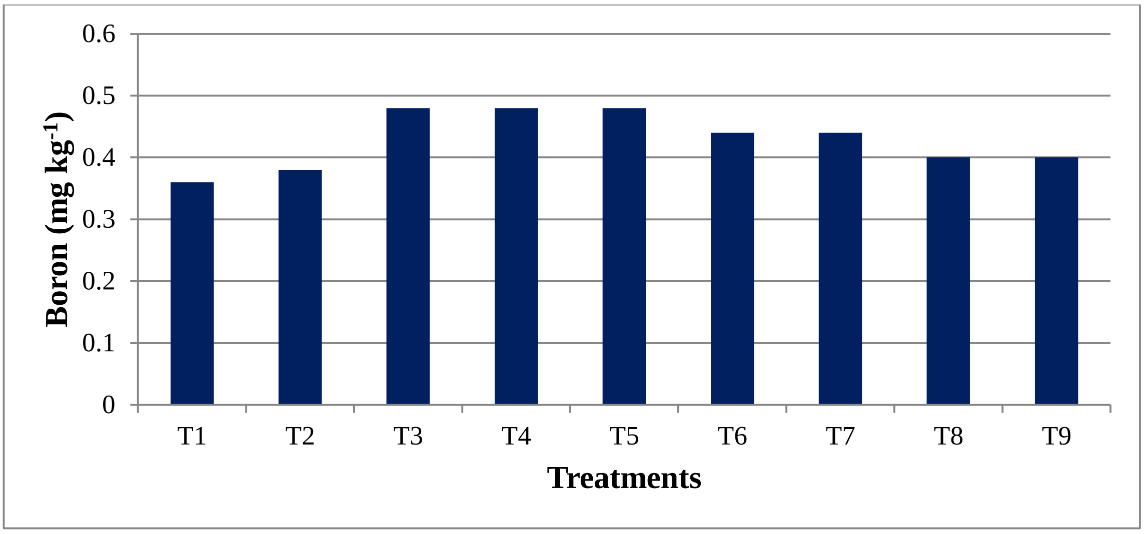


Fig.5.47: Effect of treatments on boron content in post- harvest soil

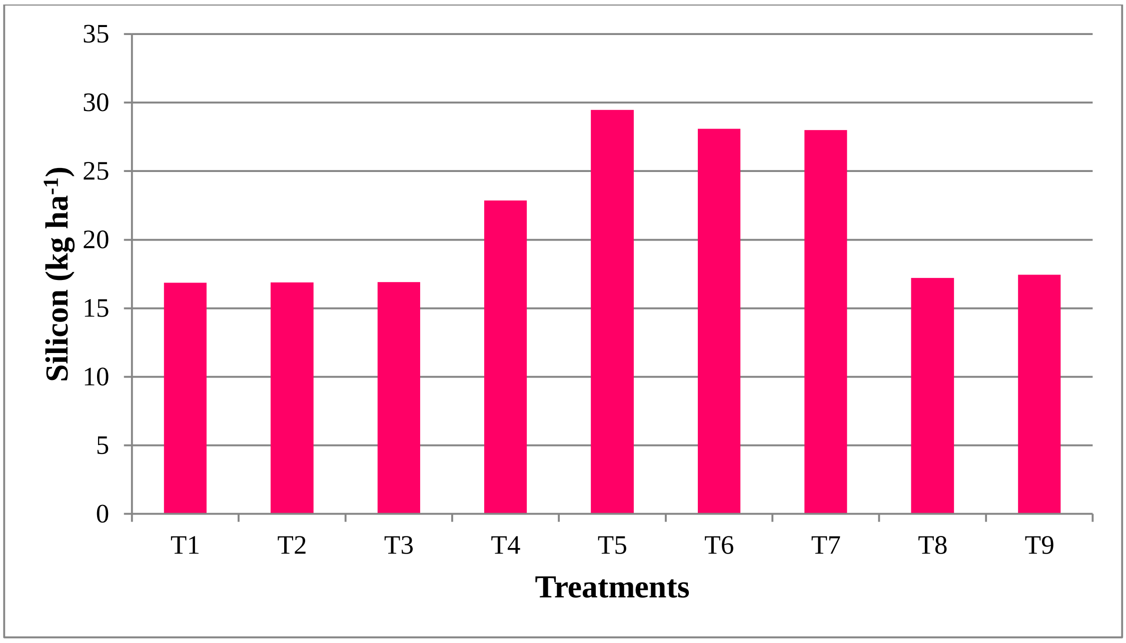


Fig.5.48: Effect of treatments on silicon content in post-harvest soil

Among the treatments, T_5 (soil test based nutrient recommendation + vermicomposted rice straw at 5 t ha^{-1}) registered higher calcium (120.34 mg kg^{-1}) and magnesium (27.17 mg kg^{-1}) content. Application of vermicomposted rice straw along with inorganic fertilizers seemed to be effective in enhancing the calcium and magnesium status of experimental soil and it might be due to higher content of calcium and magnesium in vermicomposted rice straw.

Significantly higher sulphur content (4.85 mg kg^{-1}) was noted in T_5 receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw at 5t ha^{-1}. This might be due to the contribution of sulphur in fertilizers and vermicomposted rice straw to the soil available pool.

Regarding micronutrients, the content of iron, manganese, zinc, copper, boron, and that of beneficial element silicon were found to be highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw at 5 t ha^{-1}). The higher micronutrient status in vermicomposted rice straw and increased microbial activity upon its application resulted in its increase in experimental soil. As expected, nutrient status of absolute control was lowest.

5.3.3. Fractionation

Nutrient transformation is a continuous process and is mediated through chemical and biochemical process. The change of one form of nutrient to another is termed as nutrient dynamics. The understanding of dominant forms or fractions of each nutrient is important in managing the fertility level of these nutrients for rice.

5.3.3.1. Carbon fractions

The fractions of carbon in the experimental field were studied at different stages *viz.*, before planting, at tillering and panicle initiation. Water soluble carbon (WSC), hot water extractable carbon (HWEC), microbial biomass carbon (MBC), permanganate oxidizable carbon (POXC), and total carbon constituted the various fraction of carbon analysed. Of the different fractions, POXC contributed largely to total carbon followed by HWEC, MBC, and WSC.

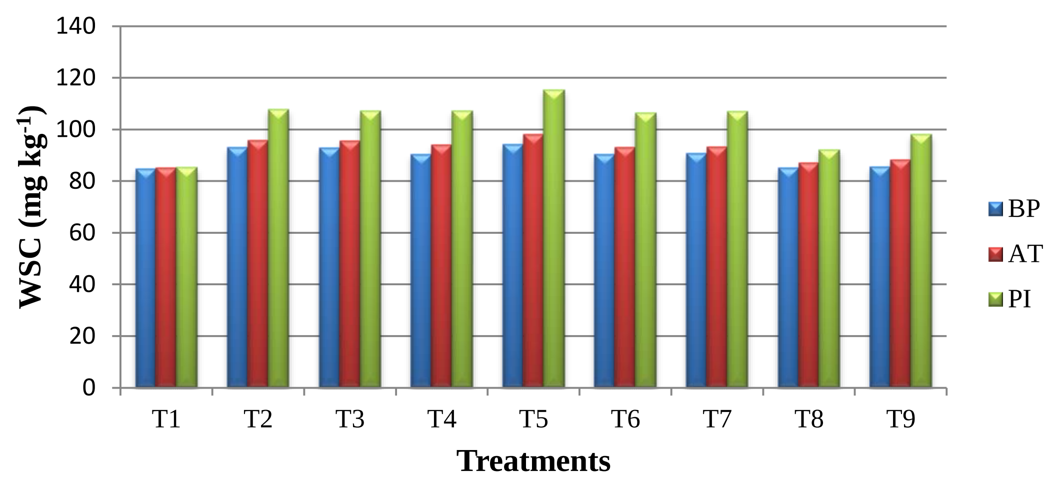


Fig.5.49: Water soluble carbon (WSC) at different stages of crop

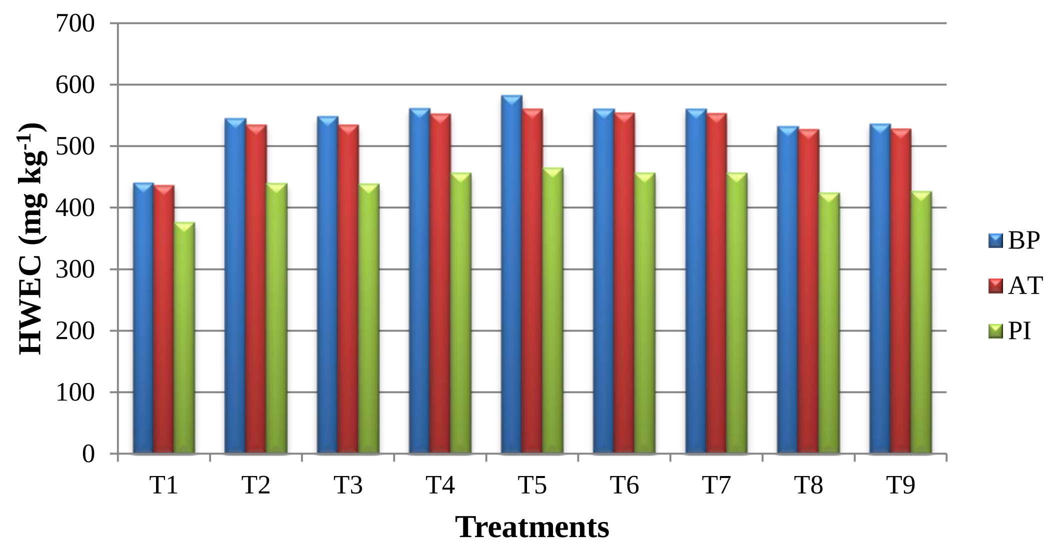


Fig.5.50: Hot water extractable carbon (HWEC) at different stages of crop

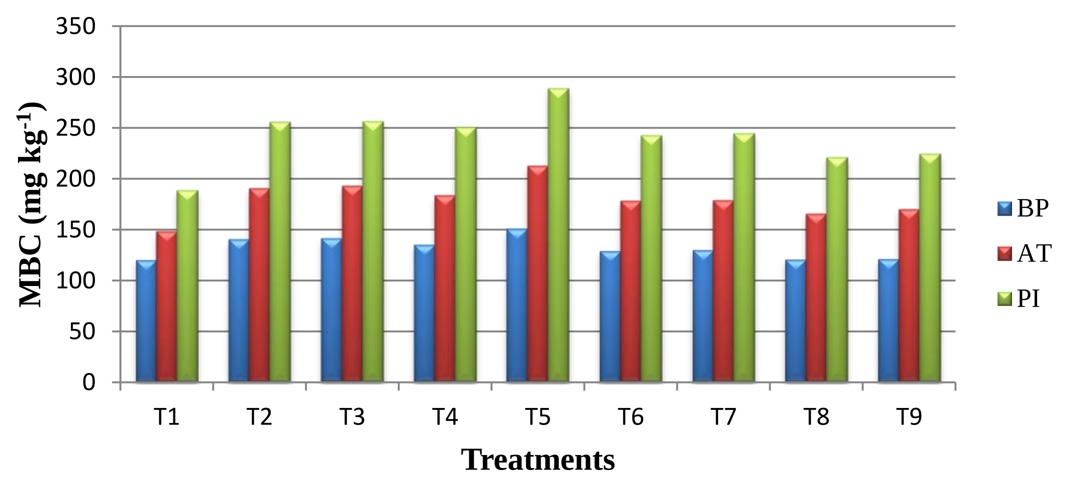


Fig.5.51: Microbial biomass carbon (MBC) at different stages of crop

It is the rate of decomposition of material that decides the amount of WSC in the experimental field. Soils receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw at 5 t ha^{-1} recorded the highest WSC at all the stages studied. Among the different stages, WSC was highest at panicle initiation followed by tillering stage of rice (Figure 5.49). The increase in WSC with crop growth might be due to the increased rate of decomposition of organic materials as a result of microbial proliferation as well as soil enzyme activity. The highest enzyme activity recorded in T_5 in the present study adequately supports the increase in WSC.

The HWEC was extracted after WSC using hot distilled water. Here also the treatment T_5 (soil test based nutrient recommendation + vermicomposted rice straw at 5 t ha^{-1}) registered the highest value at all the stages studied as in the case of WSC. Among the different stages studied, HWEC was found to decrease with advancement of crop growth (Figure 5.50). The HWEC constitutes the soil microbial biomass, simple organic compounds and easily hydrolysable carbon which might have decomposed and converted into WSC. This may be reason for decline in the HWEC carbon over crop growth and the corresponding increase in the WSC. The results are in agreement with the findings of Demise *et al.* (2014).

The MBC is the labile pool in the soil and it determines the nutrient availability and productivity of agro ecosystem. From the results it could be inferred that MBC was highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw at 5 t ha^{-1}) and lowest in T_1 (absolute control) at all the stages. Another noticeable feature was the increased MBC at panicle initiation than at tillering and before planting (Figure 5.51). This might be due to increased microbial activity at panicle initiation stage.

Permanganate oxidizable carbon (POXC) constituted all readily oxidizable organic components including humic materials and polysaccharides. The content of POXC reflects relatively stabilized pool of active soil carbon (Culman *et al*., 2012). At all the stages, plots that received combined application of soil test based nutrient recommendation and vermicomposted rice straw at 5 t ha^{-1} (T_5) registered higher content and lowest values were associated absolute control (T_1). From the figure 5.52, it could be inferred that the POXC content showed a decrease in value with the advancement of crop growth. The increased microbial activity and the mineralisation that followed might have resulted in the depletion of POXC.

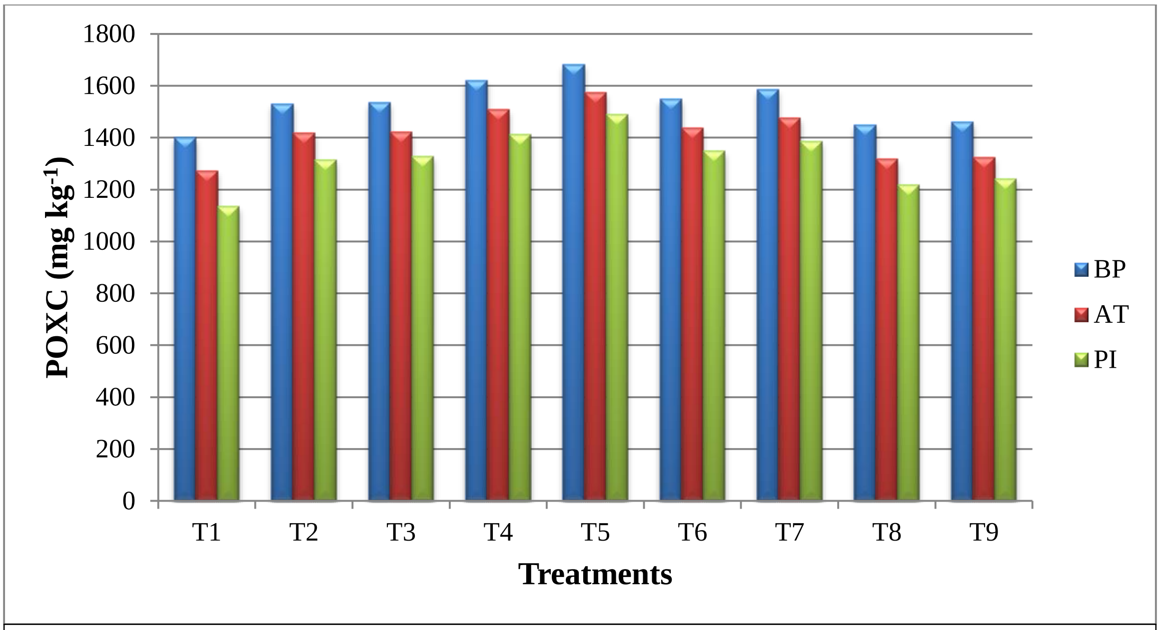


Fig.5.52: Permanganate oxidizable carbon (POXC) at different stages of crop

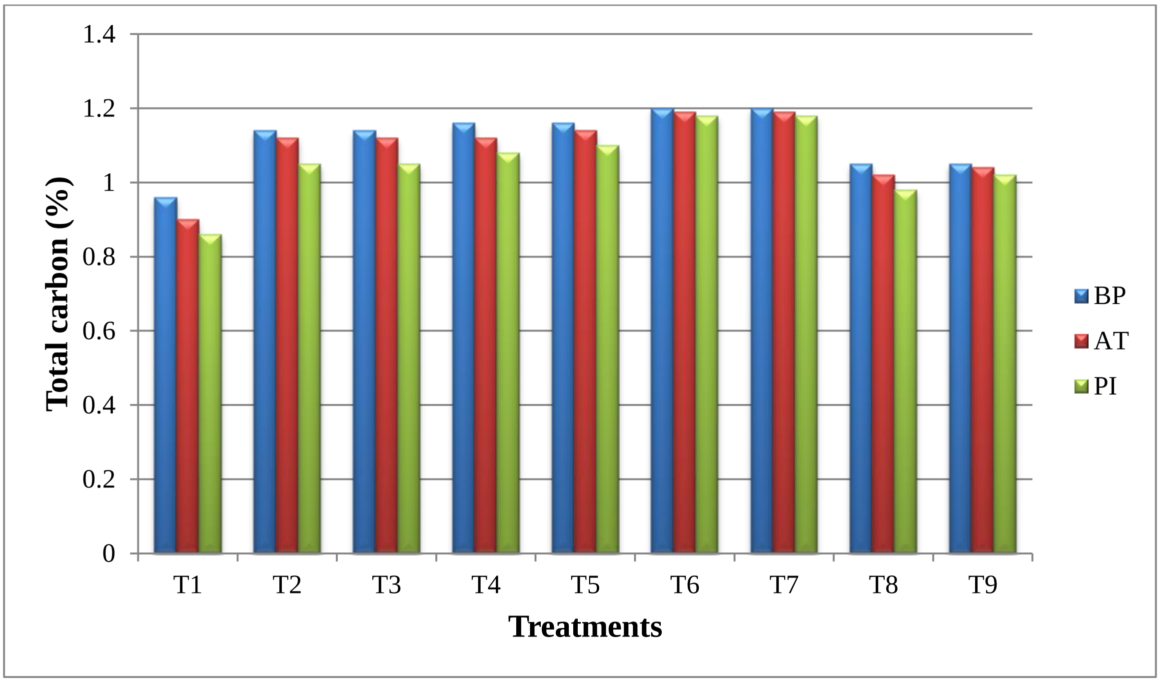


Fig.5.53: Total carbon at different stages of crop

Considering the treatment effect, it was seen that the soil test based nutrient recommendation and biochar at 5 t ha^{-1} (T_6 and T_7) recorded significantly higher value followed by plots receiving soil test based nutrient recommendation and vermicomposted rice straw (T_5). The highly carbonaceous nature of biochar (rice straw biochar and rice husk biochar) was responsible for the higher content of total carbon in T_6 and T_7. Absolute control (T_1) registered the lowest value for the fraction of total carbon at all the crop stages studied (Figure 5.53). A perusal of total carbon value in the field experiment showed that the content decreased at tillering and panicle initiation than the values before planting. However, the percentage decrease in total carbon with the advancement in crop growth was lowest in biochar amended plots (T_6 and T_7) and this is due to the presence of recalcitrant carbon in the rice straw biochar and rice husk biochar as evidenced from the FT-IR spectra of present study.

5.3.3.2. Nitrogen fractions

Nitrogen is most dynamic in nature and it exists in several forms in soil. The dominant nitrogen fraction in soil is in the organic form. Whereas, plant depends on the inorganic nitrogen source but it accounts the lowest in soil. Among the inorganic nitrogen fractions, ammoniacal nitrogen is the most abundant form in submerged conditions. Organic nitrogen fractions namely total hydrolysable nitrogen and amino acid nitrogen and inorganic nitrogen fractions namely ammoniacal nitrogen and nitrate nitrogen were estimated in the present study.

The treatments, soil test based nutrient recommendation along with rice straw biochar, rice husk biochar, vermicomposted rice straw were comparable in terms of total hydrolysable nitrogen (THN) in registering higher values of 2296.35 mg kg^{-1}, 2285.10 mg kg^{-1}, and 2274.84 mg kg^{-1} respectively before planting rice crop. This might be due to the presence of organic sources in these treatments and also higher pH after the addition of organic materials. The results are in conformity with the findings of Nideesh (2019). At tillering stage, statistically higher THN was found in soil test based nutrient recommendation along with biochar treatments (T_6 and T_7). At panicle initiation stage, T_7 receiving combined application of soil test based nutrient recommendation and rice straw biochar recorded higher THN (2168.06 mg kg^{-1}). At all stages, absolute control (T_1) registered lowest value. With advancement of crop growth, THN was decreased irrespective of the treatments. This might be due to the mineralisation of organic sources in the soil.

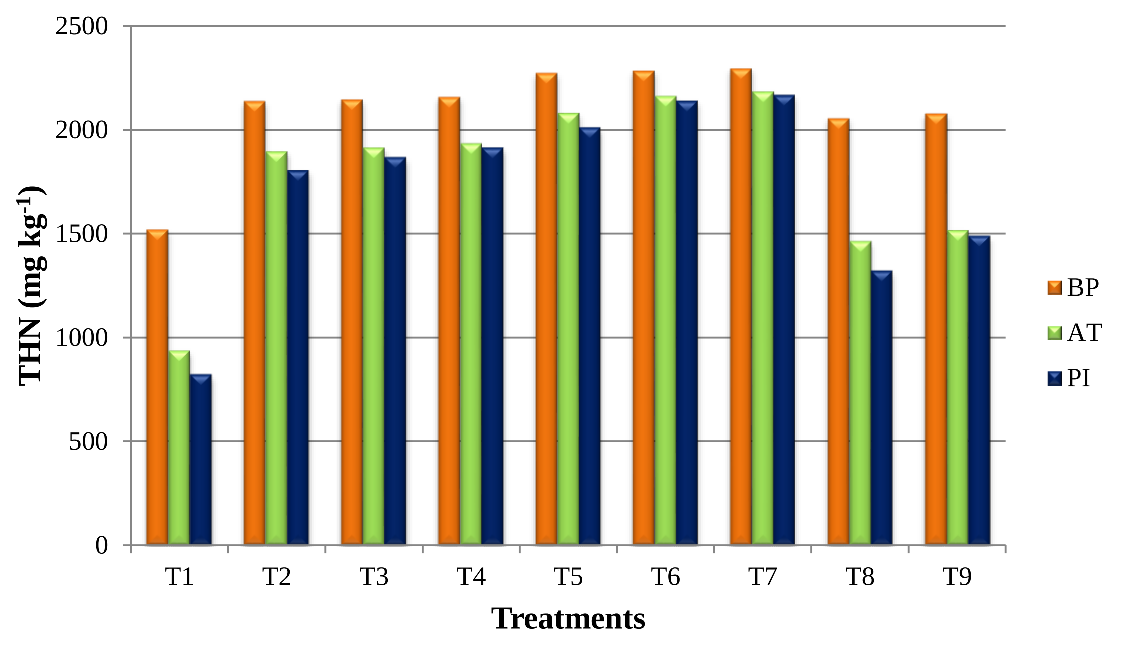


Fig.5.54: Total hydrolysable nitrogen (THN) at different stages of crop

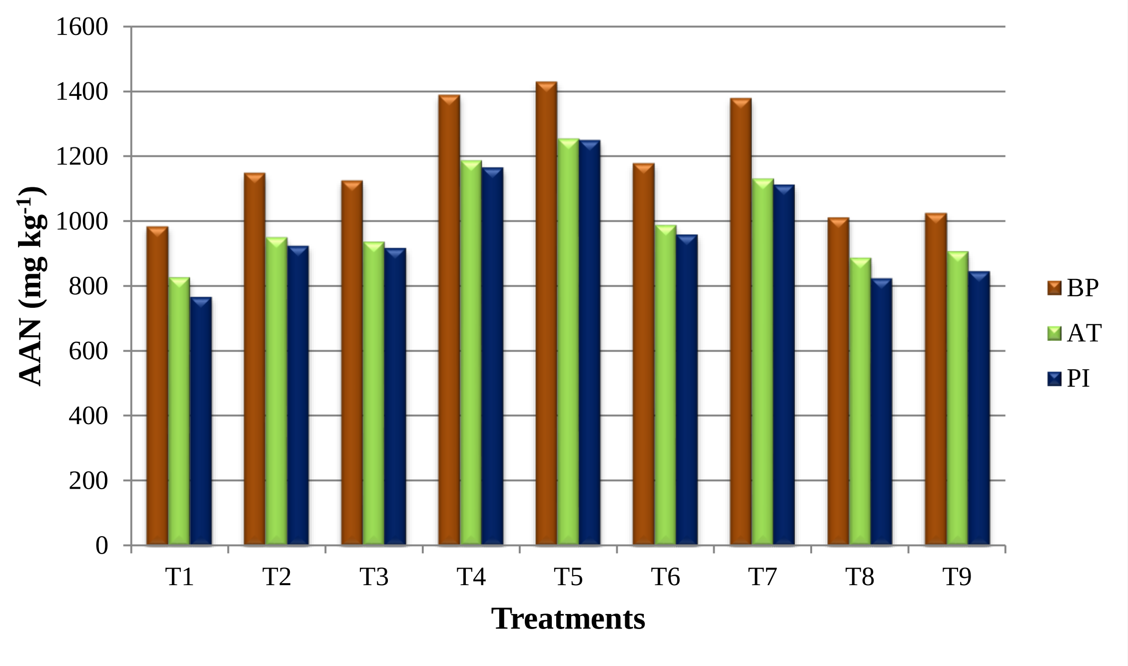


Fig.5.55: Amino acid nitrogen (AAN) at different stages of crop

Treatments had a promising effect on amino acid nitrogen (AAN) content which was highest in plots receiving soil test based nutrient recommendation and vermicomposted rice straw at all stages *viz*., before planting, at tillering, and panicle initiation. As always absolute control registered the lowest value.

With the advancement of crop growth AAN was found to decrease and this might be due to the mineralisation of nitrogen, which denotes the conversion of organic nitrogen into inorganic nitrogen (Figure 5.55). Nitrogen availability is important for the growth of plant and it is closely associated with the mineralization of soil organic nitrogen and the depolymerisation of the nitrogen containing constituents. Due to higher turnover rate, soil amino acids are rapidly mineralized and immobilized by soil microorganisms and hence it is an important storage pool for immobilized N and a dominant transitional available N form (Lu *et al*., 2018).

Before planting, ammoniacal nitrogen fraction was higher in the treatments, soil test based nutrient recommendation + vermicomposted rice straw (57.86 mg kg^{-1}) and Adhoc KAU organic POP (57.75 mg kg^{-1}), which were on par statistically. While comparing the content of ammonical nitrogen at different stages, it was found to decrease at tillering irrespective of the treatments and it might be due to the immobilization or crop uptake (Figure 5.56). At tillering, significantly higher ammoniacal nitrogen was found in the treatments, soil test based nutrient recommendation + vermicomposted rice straw (52.65 mg kg^{-1}), Adhoc KAU organic POP (52.13 mg kg^{-1}) and soil test based nutrient recommendation+ FYM (52.01 mg kg^{-1}). Ammonical nitrogen fraction at panicle initiation was higher than that at tillering and statistically higher content was recorded in soil test based nutrient recommendation+ vermicomposted rice straw (54.81 mg kg^{-1}).

The nitrate nitrogen fraction was higher in plots receiving combined application of soil test based nutrient recommendation+ vermicomposted rice straw at all the stages studied and values are 38.16 mg kg^{-1} before planting, 32.14 mg kg^{-1} at tillering, and 30.08 mg kg^{-1} at panicle initiation. Absolute control recorded the lowest content at all the stages. With the advancement of crop growth, the content of nitrate nitrogen found to decrease and this might be due to the anaerobic environment as well as denitrification occurring under submerged condition (Figure 5.57).

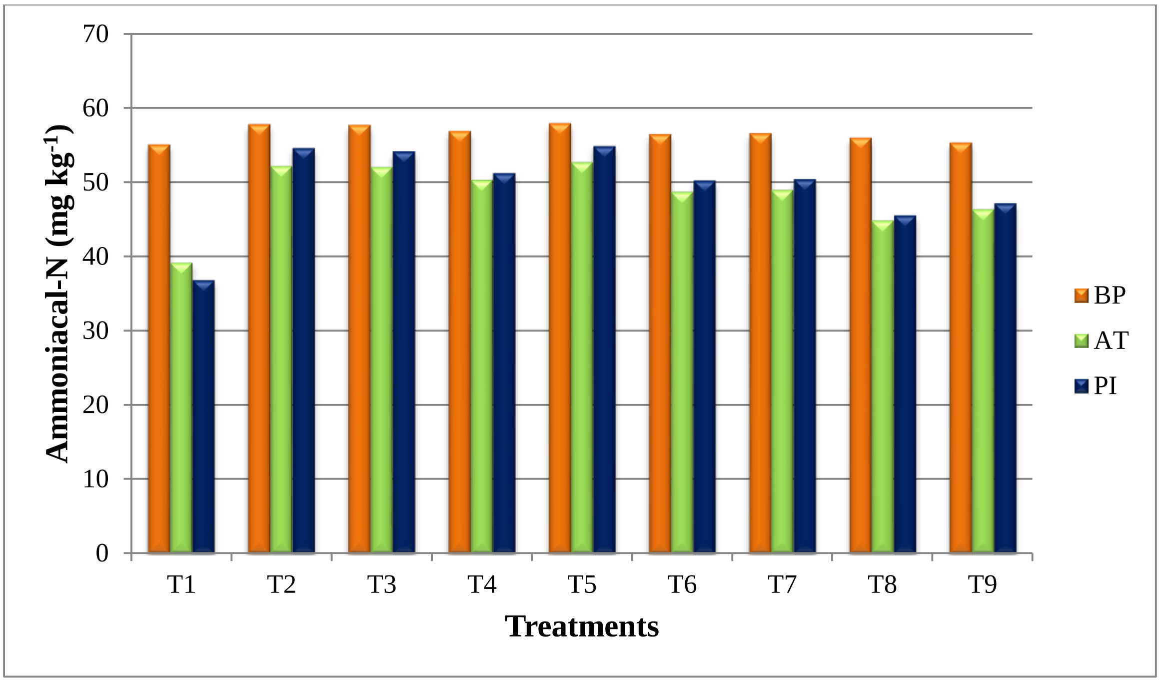


Fig.5.56: Ammoniacal nitrogen at different stages of crop

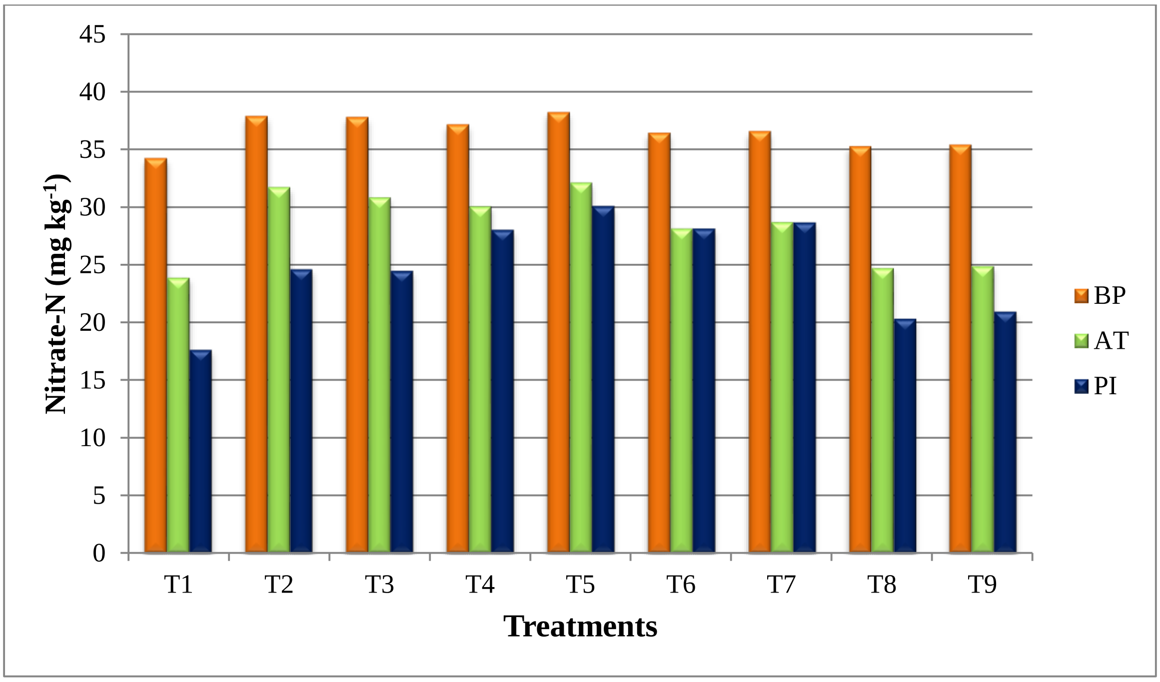


Fig.5.57: Nitrate nitrogen at different stages of crop

5.3.3.3. Phosphorus fractions

The phosphorus fractions namely soluble-P, aluminium bound phosphorus (Al- P), iron bound phosphorus (Fe-P), Sesquioxide occluded P, calcium bound phosphorus (Ca-P), and organic-P were analysed at different stages of crop *viz*., before planting, at tillering, and panicle initiation. Organic-P was dominant in all the treatments than inorganic-P fractions. Among the inorganic fractions, Fe-P was dominant followed by sesquioxide occluded-P. The major fractions which contributed to available phosphorus in soil under submerged condition were Fe-P, Al-P, sesquioxide occluded-P. The decrease in the above mentioned fractions were counterpoised by the corresponding increased Ca-P with the advancement of crop growth.

The soluble-P fraction was highest in treatments T_5 (21.23 mg kg^{-1}) and T_3 (20.20 mg kg^{-1}), and were statistically on par. At tillering, treatments T_5 (23.12 mg kg^{-1}) and T_3 (22.68 mg kg^{-1}) are higher in soluble-P. At panicle initiation, T_5 (22.51 mg kg^{-1}) registered highest soluble-P fraction. At all stages, absolute control recorded lowest soluble-P. Among the different stages, soluble-P was found to be increased at tillering followed by a decrease at panicle initiation in all the treatments except absolute control in which the soluble-P was found to be decreased at tillering and panicle initiation stage of rice (Figure 5.58). The increase in soluble-P at tillering might be due to the release of soluble or loosely bound phosphorus from the mineralisation of organic materials in the treatments and further decrease at panicle initiation might be because of fixation.

Aluminium bound phosphorus was highest in T_5 at all stages and are 18.00 mg kg^{-1} before planting, 16.86 mg kg^{-1} at tillering, and 14.28 mg kg^{-1} at panicle initiation stage of rice. Absolute control (T_1) registered lowest content of Al-P. The dominant inorganic-P fraction Fe-P also followed similar trend as that of Al-P. The value of Fe-P was 141.81 mg kg^{-1} before planting, 140.52 mg kg^{-1} at tillering, and 138.86 mg kg^{-1} at panicle initiation stage in T_5 and was highest than that of other treatments. With the advancement of crop growth, Al-P and Fe-P were found to be decreased irrespective of the treatments (Figure 5.59-60).

Treatment T_6 registered highest fraction of sesquioxide occluded-P before planting as well as at tillering. At panicle initiation, treatments T_6 and T_7 are highest in their sesquioxide occluded-P and are statistically on par. Absolute control recorded lowest sesquioxide occluded-P. With advancement of crop growth sesquioxide occluded-P was found to decrease (Figure 5.61).

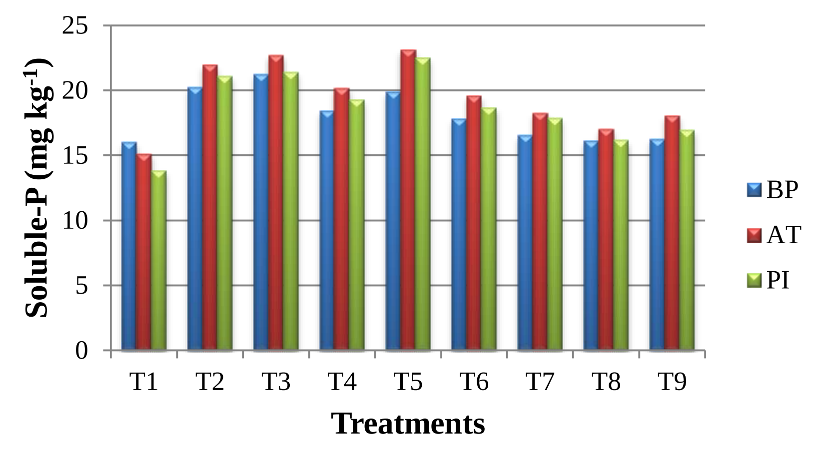


Fig.5.58: Soluble-P at different stages of crop

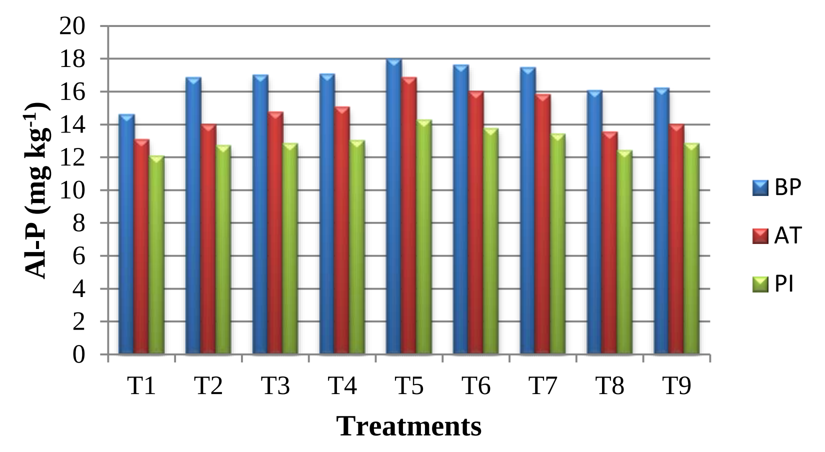


Fig.5.59: Aluminium bound phosphorus at different stages of crop

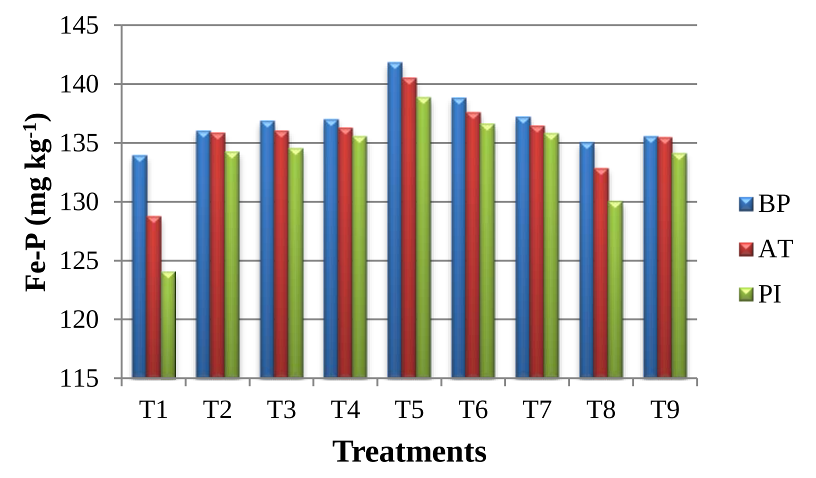


Fig.5.60: Iron bound phosphorus at different stages of crop

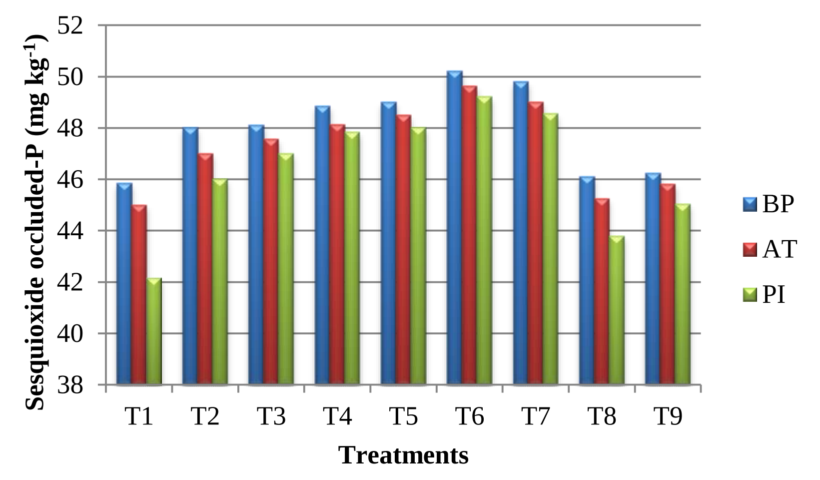
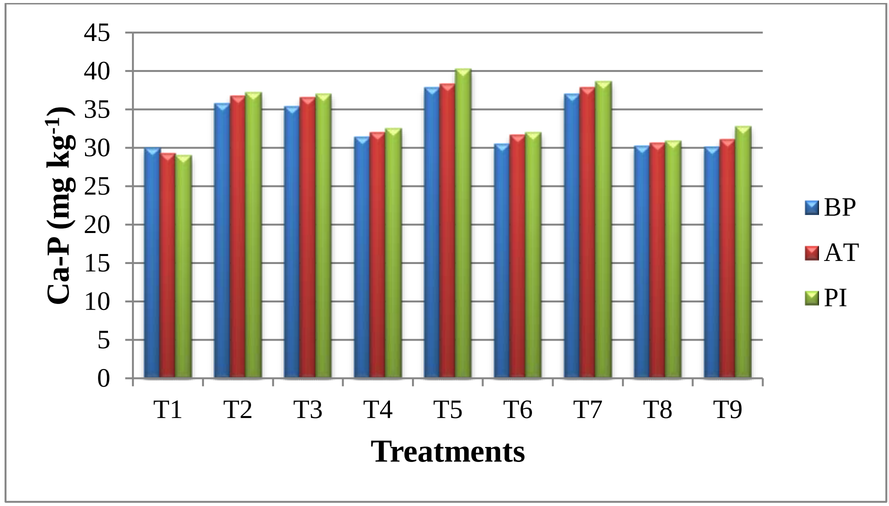


Fig.5.61: Sesquioxide occluded-P at different stages of crop



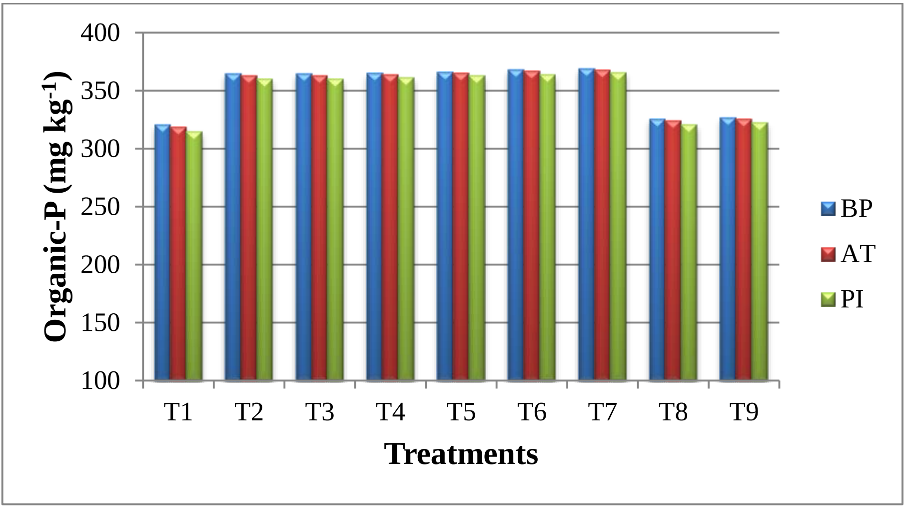


Fig.5.62: Calcium bound phosphorus at different stages of crop

Fig.5.63: Organic-P at different stages of crop

The Ca-P fraction was found to be increased with advancement of crop growth in all treatments except absolute control. At tillering, treatments T_5 (37.81 mg kg^{-1}) and T_7 (37.00 mg kg^{-1}) are statistically superior in their Ca-P than that in other treatments. At tillering as well as panicle initiation stage, T_5 recorded higher value. The lowest content of Ca-P was found in T_1.

Before planting as well as at tillering, organic-P fraction was statistically highest in treatments T_7 and T_6. At panicle initiation, T_7 registered highest organic-P fraction. The increased organic-P in biochar amended soils might be due to the carbonaceous nature of biochar. As always T_1 recorded lowest value of organic-P fraction. Of the different stages, organic-P was found to be decreased at tillering as well as panicle initiation compared to the fraction present in soil before planting (Figure 5.63).

5.3.3.4. Potassium fractions

The effect of treatments on potassium fractions namely water soluble-K and exchangeable-K were studied at different stages *viz*., before planting, at tillering and panicle initiation. The readily exchangeable-K as well as water soluble-K contributed to available-K.

The water soluble-K was highest in T_7 (soil test based nutrient recommendation+ rice straw biochar) at all the stages and the value are 26.50 mg kg^{-1} before planting, 38.10 mg kg^{-1} at tillering, and 47.21 mg kg^{-1} at panicle initiation. The higher water soluble-K in T_7 might be due to the higher potassium content in rice straw biochar as evidenced from the results of characterization experiment. The increase in water soluble-K at tillering and panicle initiation might be due to the release of potassium from other potassium fractions (Figure 5.64).

The exchangeable-K also followed similar trend as that of water soluble-K. The content of exchangeable-K was 138.52 mg kg^{-1} before planting, 164.98 mg kg^{-1} at tillering and 184.51 mg kg^{-1} at panicle initiation stage. With advancement of crop growth exchangeable-K was found to be increased and this might be due to the transformation of potassium fractions to exchangeable pool (Figure 5.65).

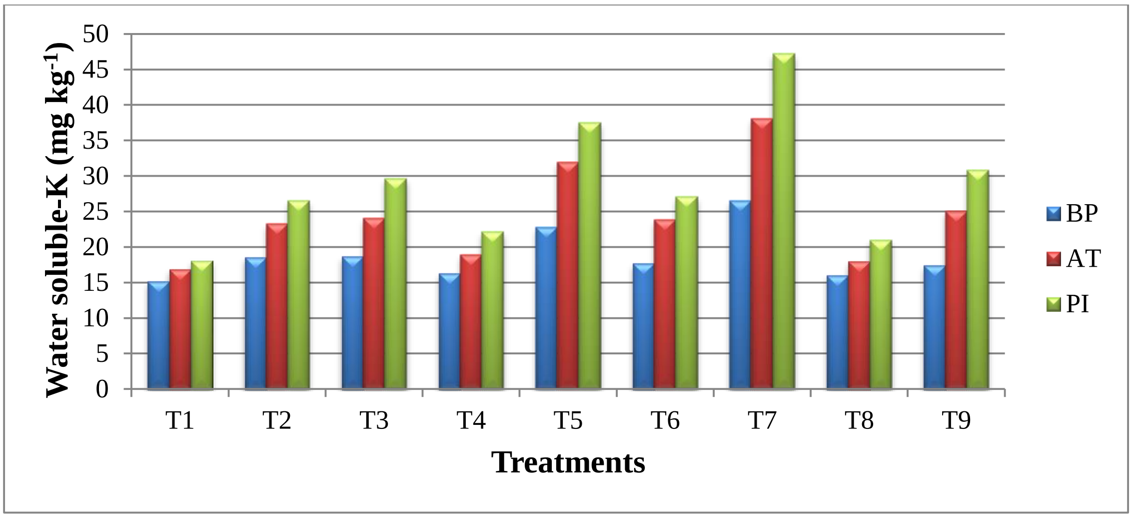


Fig.5.64: Water soluble-K at different stages of crop

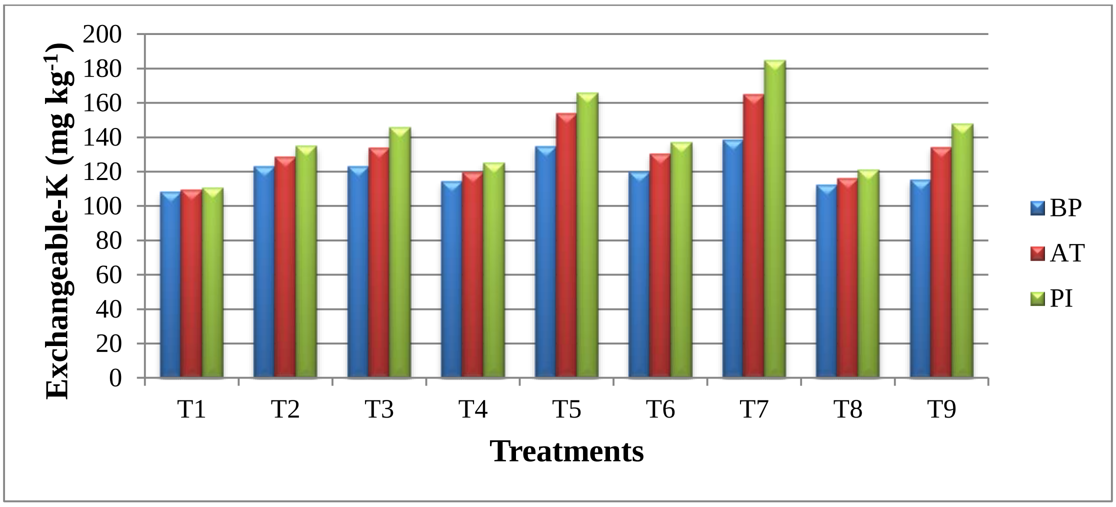


Fig.5.65: Exchangeable-K at different stages of crop

5.3.3.5. Calcium fractions

The effect of different treatments on calcium fractions in soil were studied before planting, at tillering, and at panicle initiation (Figure 5.66-67). The content of exchangeable calcium was more than the water soluble calcium.

The treatment T_5 (soil test based nutrient recommendation + vermicomposted rice straw) registered higher water soluble-Ca at all stages. The increase in water soluble calcium in soils of T_5 might be due the application of lime as well as greater calcium content in vermicomposted rice straw. Absolute control (T_1) was lowest in water soluble-Ca and this might be due to the lack calcium sources in T_1 compared to other treatments.

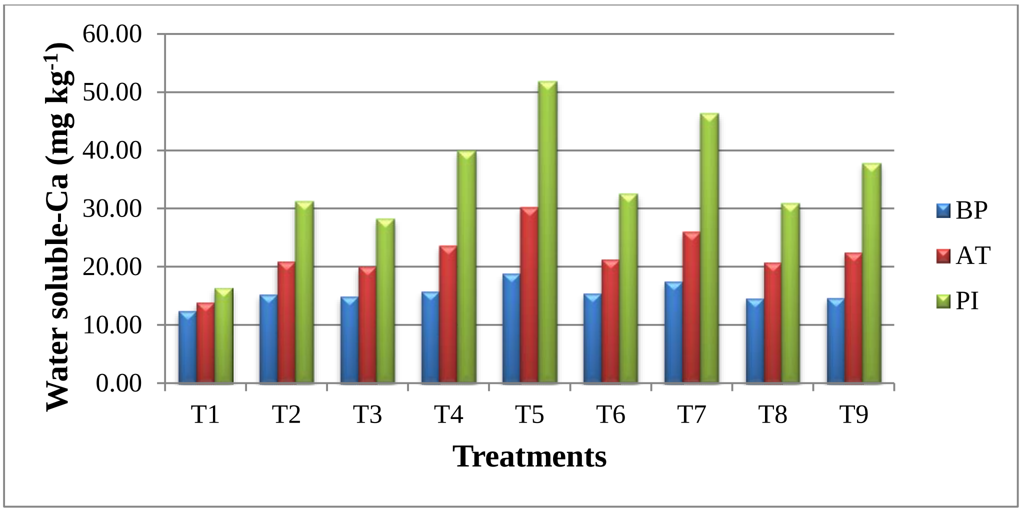


Fig.5.66: Water soluble-Ca at different stages of crop

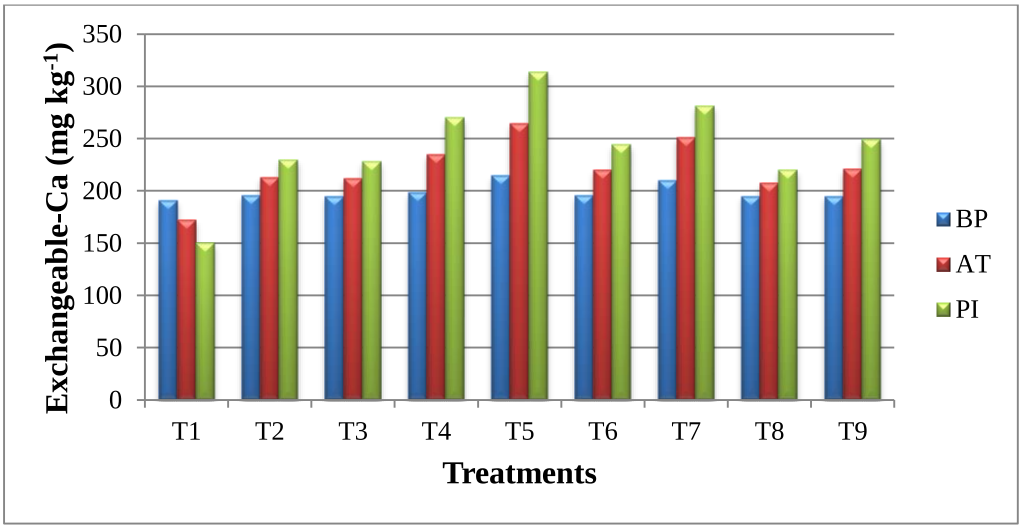


Fig.5.67: Exchangeable-Ca at different stages of crop

The increase in water soluble calcium with advancement of crop growth in T_1 was counterpoised by the decrease in exchangeable calcium as manifested from the present study.

The exchangeable calcium fraction also recorded the highest value in T_5 and lowest in T_1 at all the stages. Application of lime and decomposition of added organic materials resulted to an increase in the exchangeable calcium fraction in all the treatments at tillering as well as panicle initiation except in T_1. The decrease in exchangeable fraction with crop growth in T_1 might be due the lack of calcium sources and also the transformation of exchangeable fraction to water soluble pool at tillering and panicle initiation.

5.3.3.6. Magnesium fractions

The content of water soluble and exchangeable -Mg fractions at different stages of crop was studied to assess the impact of treatments (Figure 5.68-69). It could be seen that among the treatments, T_5 (soil test based nutrient recommendation+ vermicomposted rice straw) registered higher magnesium fractions at all stages whereas T_1 (absolute control) the lowest.

Water soluble-Mg increased with the advancement crop growth in all the treatments. This might be due to the release of magnesium either from the exchangeable fraction or from the decomposition of added organic materials or from the application of magnesium sulphate. As there was no external sources in absolute control, increase in water soluble fraction might be from the other magnesium fractions in soil.

The exchangeable-Mg was found to decrease with crop growth in T_1 due to the lack of external inputs and also by the release of magnesium from exchangeable pool to available form. In other treatments, an increase in exchangeable fraction was noticed at tillering and this might be because of the magnesium sulphate addition after transplanting rice and as well as from the release of magnesium from the decomposition of added organic materials.

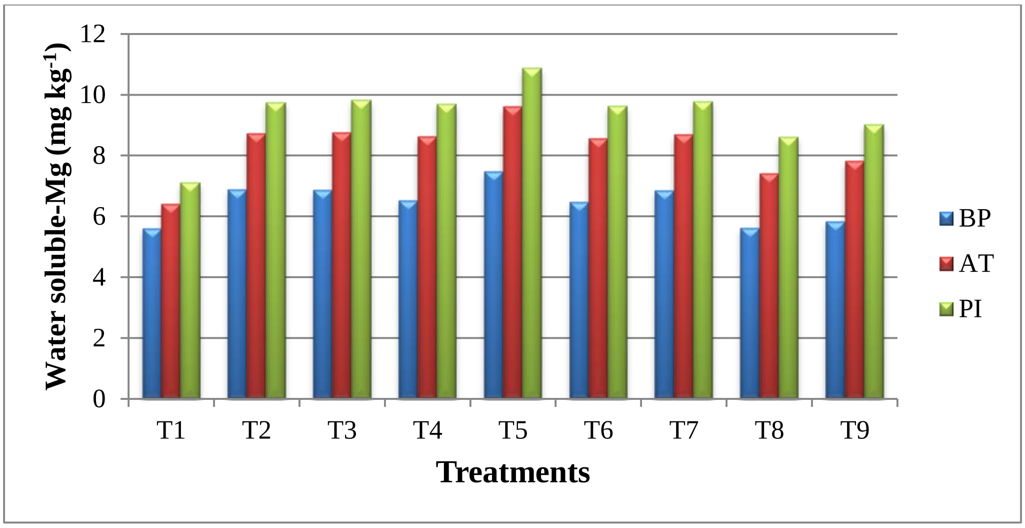


Fig.5.68: Water soluble-Mg at different stages of crop

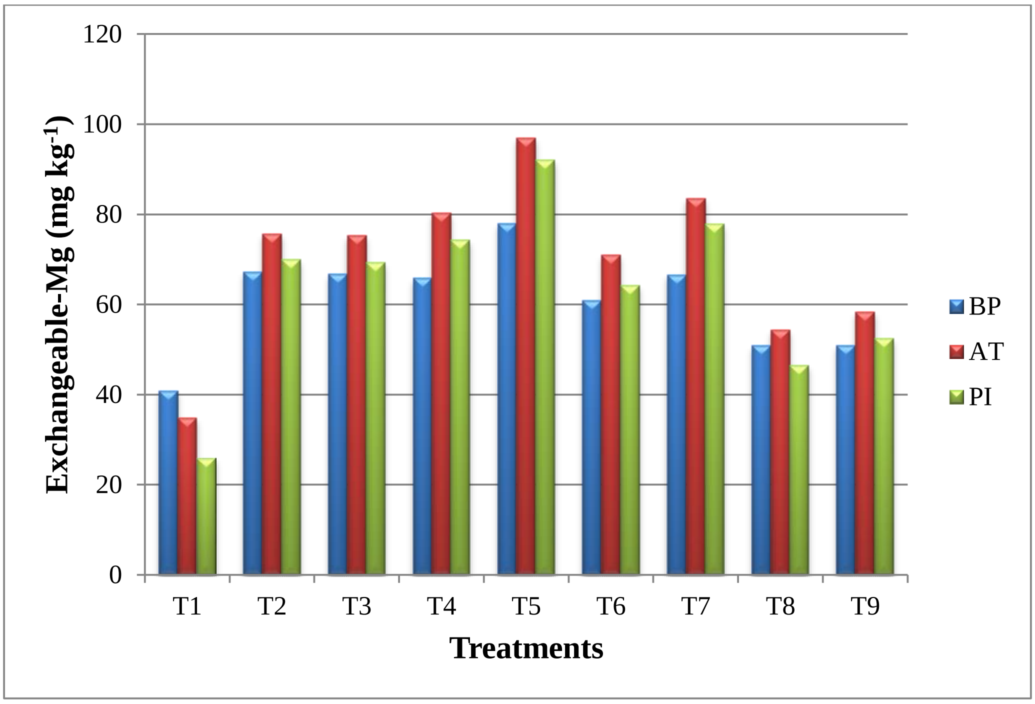


Fig.5.69: Exchangeable-Mg at different stages of crop

5.3.3.7. Sulphur fractions

The effect of treatments on sulphur fractions *viz.*, organic and available sulphur were studied at different stages of crop growth (Figure 5.70-71). Organic sulphur fraction contributed more to total sulphur than the available sulphur.

No significant difference could be noticed between organic sulphur content before planting. However application of treatments significantly influenced the available sulphur fraction.

At tillering stage, sulphur fractions were statistically highest in treatments T_5 and T_4, which are on par. Lowest sulphur fractions are found in T_1. At panicle initiation stage, organic and available sulphur was highest in T_5.

Organic sulphur decreased with advancement of crop growth in T_1. This may be due to the mining of organic sulphur to meet out the crop requirement being the only source in T_1 with respect to nutrient availability. Whereas in other treatments, organic sulphur got increased, which may be due to its release from the applied inorganic fertilizers and that from decomposition of added organic materials.

The decrease in available sulphur with crop growth irrespective of treatments might be due to the depletion of sulphur as a result of crop uptake or due to the reduction of sulphate sulphur under submerged condition.

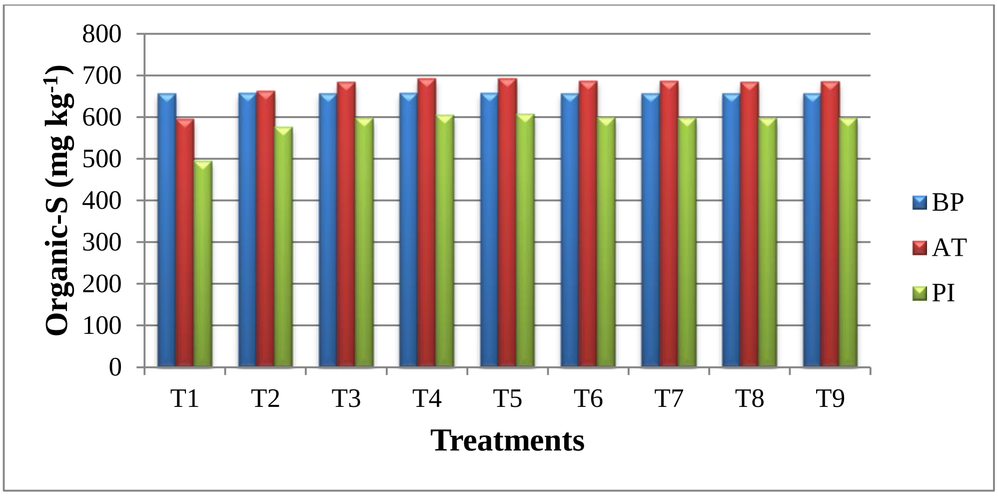


Fig.5.70: Organic-S at different stages of crop

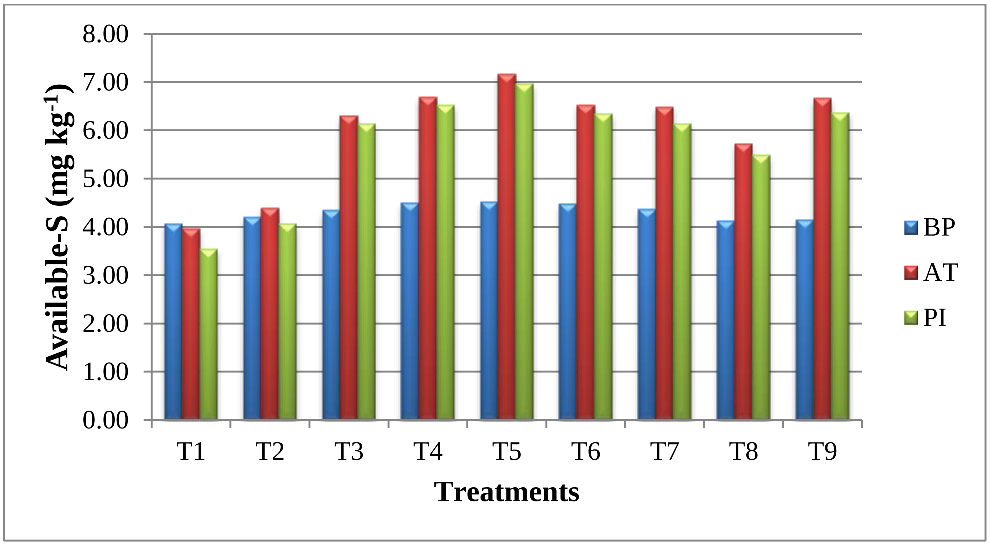


Fig.5.71: Available-S at different stages of crop

5.3.3.8. Silicon fractions

The silicon fractions namely mobile-Si, adsorbed-Si, organic-Si, occluded-Si, amorphous-Si, and residual-Si were analysed after the application of treatments at different stages of crop *viz*., before planting, at tillering, and at panicle initiation (Figure 5.72-76). The results of silicon fractionation showed that amorphous-Si is the dominant fraction followed by residual-Si, organic-Si, occluded-Si, mobile-Si and least by adsorbed-Si. Similar trend was also observed in lateritic soil by Lekshmi (2016).

Mobile-Si fraction represents the immediately available silicon fraction of the readily soluble silicon and it was found to be highest in T_6 at all stages. This may be due to the higher silicon in rice husk biochar as signified in its characterization. With advancement of crop growth mobile-Si was found to increase in all treatments and it might be due to the release of silicon from other silicon fractions in soil.

Adsorbed-Si is the main immediate insoluble source of silicon in soil solution. Before planting as well as at tillering, the adsorbed-Si was statistically higher in treatments T_6, T_7, and T_5. At panicle initiation, biochar amended treatments T_6 and T_7 registered higher values of adsorbed-Si, which later followed decreasing trend towards panicle initiation which might be due to the release of silicon from this fraction.

Organic-Si was highest in T_6 (soil test based nutrient recommendation + rice husk biochar) followed by T_7 (soil test based nutrient recommendation + rice straw biochar) at all the stages. This might be due to the higher silicon content in rice husk biochar as evidenced from the characterisation carried out in the present study. This fraction was followed a decrease in trend with the advancement of crop growth.

Occluded-Si was highest in T_6 at all stages and it decreased with the advancement of crop growth. The application of various treatments could not produce any significant difference in amorphous-Si fraction.

The residual-Si fraction was highest in T_6 before planting as well as at tillering. At panicle initiation, residual silicon was significantly highest in T_6 and T_7.

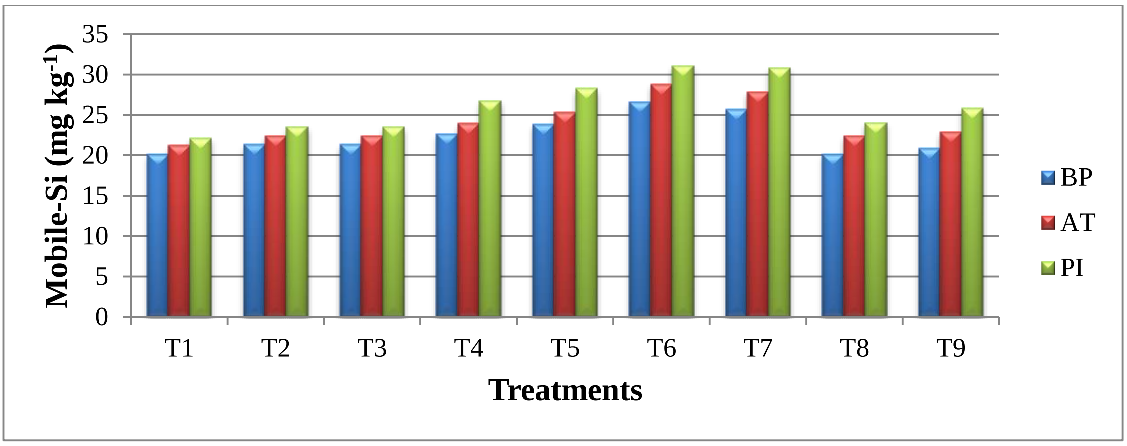


Fig.5.72: Mobile-Si at different stages of crop

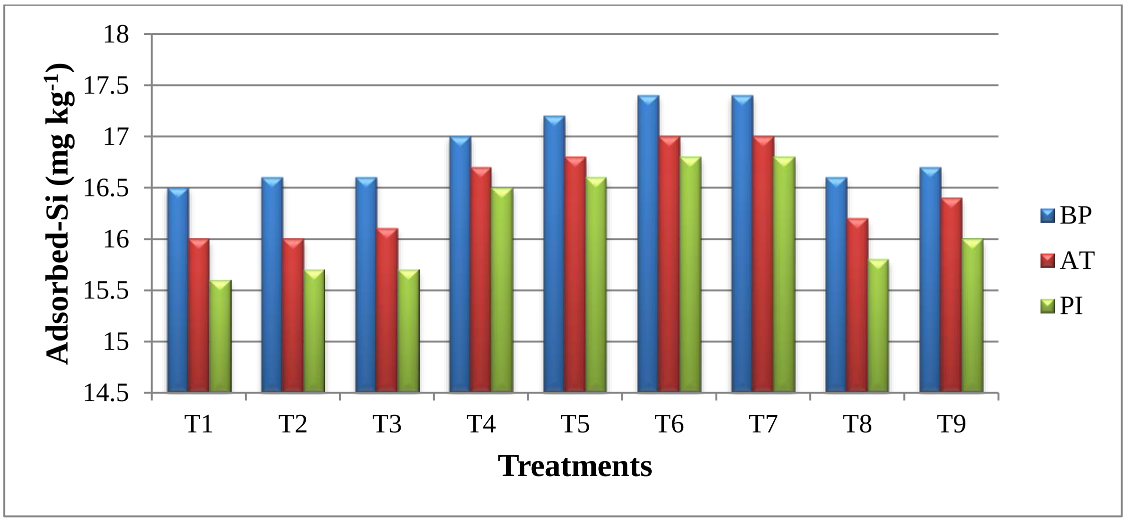


Fig.5.73: Adsorbed silicon at different stages of crop

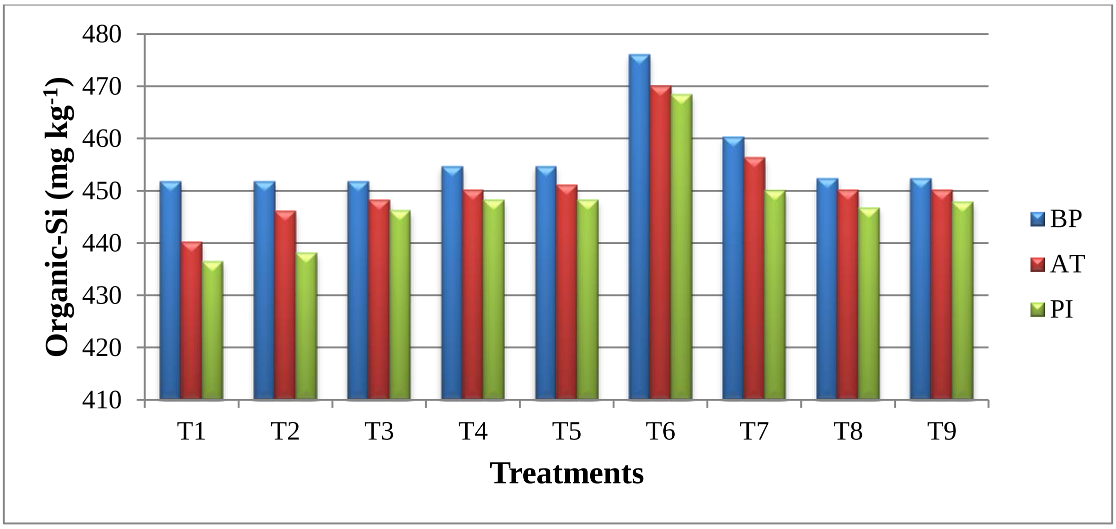


Fig.5.74: Organic silicon at different stages of crop

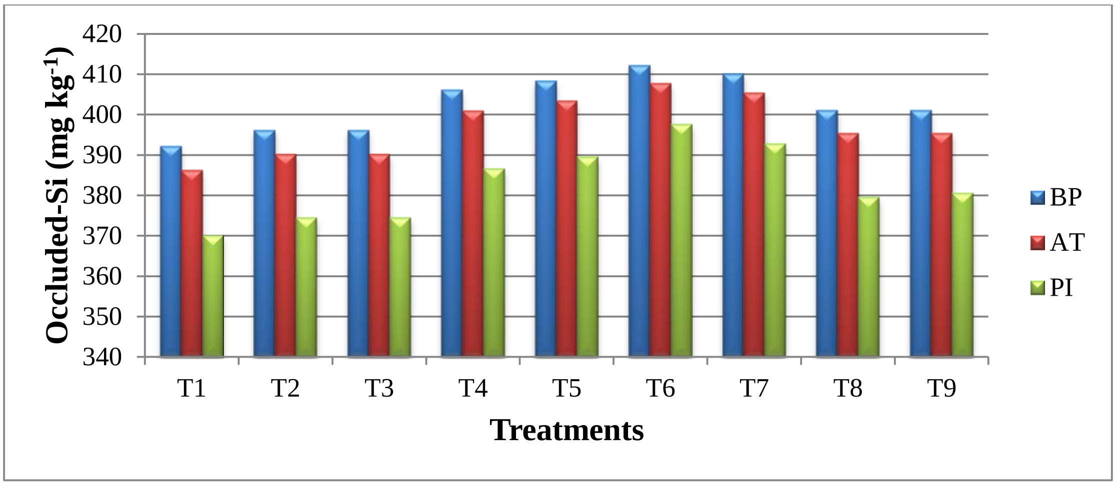


Fig.5.75: Occluded silicon at different stages of crop

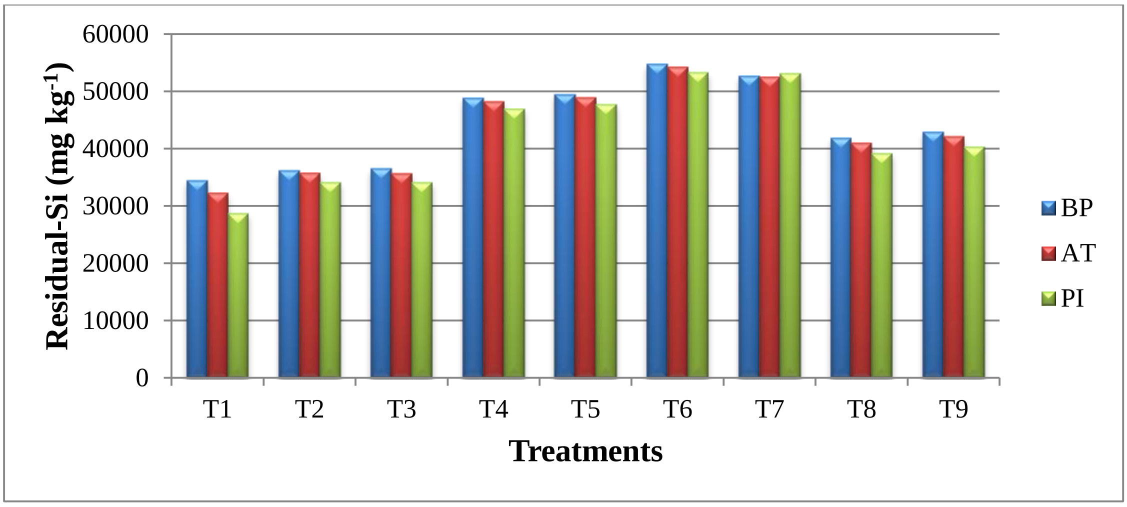


Fig.5.76: Residual silicon at different stages of crop

5.3.4 Enzyme activity

Soil enzymes exist either in free or bound form in soil and are considered as ideal indicators of soil quality with their direct involvement in nutrient cycles and thus nutrient transformations. The effects of treatments on soil enzymes namely dehydrogenase, urease, and acid phosphatase were studied at different stages of crop *viz*., before planting, at tillering, panicle initiation and at harvest.

5.3.4.1. Dehydrogenase activity

Before planting, the treatments T_5 (soil test based nutrient recommendation+ vermicomposted rice straw) and T_3 (soil test based nutrient recommendation + FYM) recorded statistically higher dehydrogenase activity than the other treatments. This might be due to the presence of easily degradable organic compounds in these treatments. Application of organic amendments significantly enhanced dehydrogenase activity possibly due to the utilization of energy in the form of carbon by microorganisms from the organic materials (Sarma *et al*., 2017). At tillering, panicle initiation and harvest, T_5 recorded highest dehydrogenase activity. Lower dehydrogenase activity was registered by T_1 (absolute control) compared to other treatments because of lack of any external inputs in these plots.

Dehydrogenase activity was found to increase upto panicle initiation followed by a decrease at harvest (Figure 5.77). Lower dehydrogenase activity at harvest was mainly due to the dry condition as well as reduced root activity that prevailed at harvest of rice. Dehydrogenase activity is strongly affected by soil moisture. When soil becomes dry, the water potential increases affecting negatively the microbial activity and thus the intracellular enzyme activity (Geisseler *et al*., 2011).

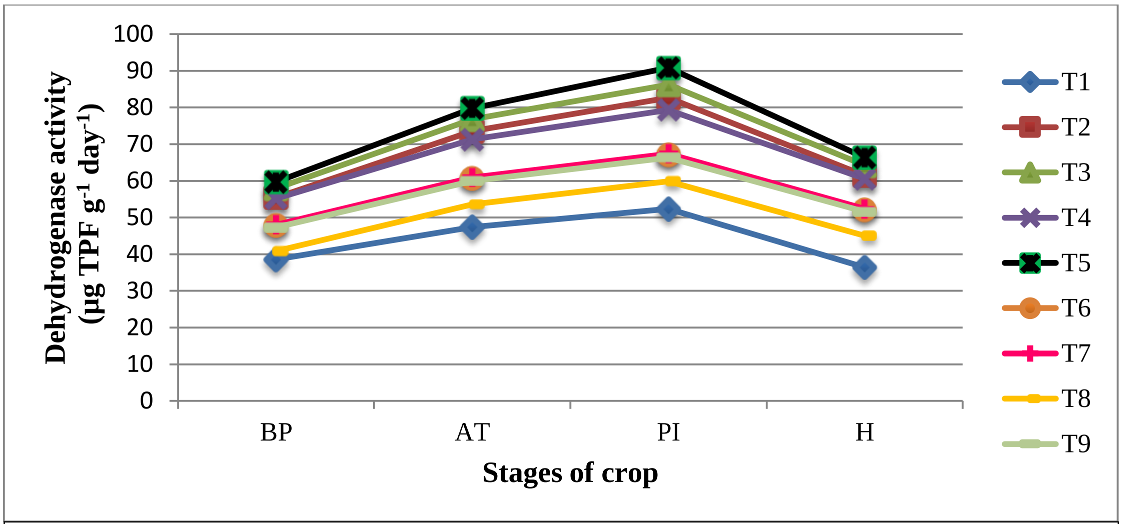


Fig.5.77: Effect of treatments on dehydrogenase activity at different stages of crop

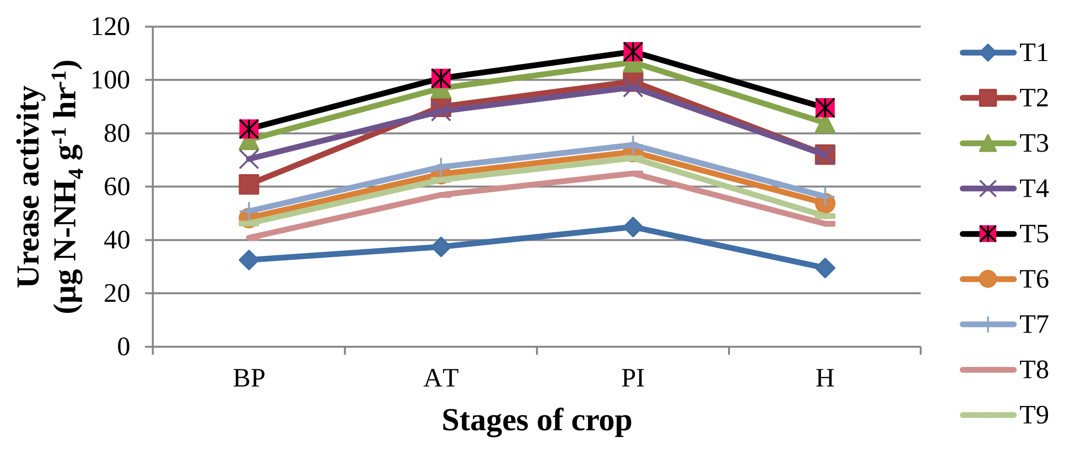


Fig.5.78: Effect of treatments on urease activity at different stages of crop

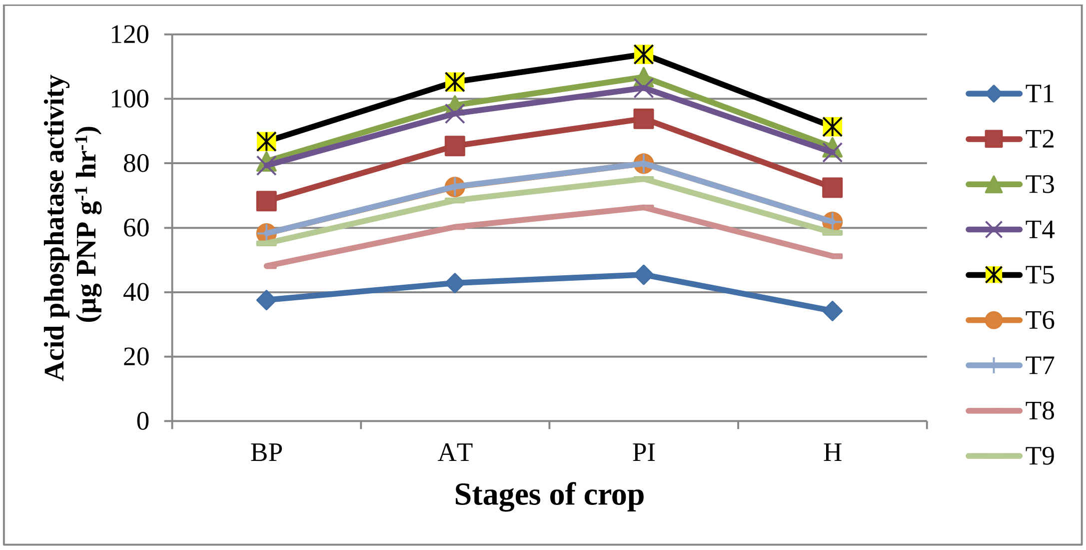


Fig.5.79: Effect of treatments on acid phosphatase activity at different stages of crop

5.3.4.2. Urease activity

Urease plays an important role in nitrogen cycling and is widely distributed in soil. The effects of treatments on urease activity at different stages of crop are depicted in Figure 5.78. Before planting, treatment T_5 (soil test based nutrient recommendation +vermicomposted rice straw) registered higher urease activity followed by T_3 (soil test based nutrient recommendation+ FYM). At tillering, urease activity in T_5 and T_3 were on par and higher than that in other treatments. This might be due to the greater availability of nitrogen resources from the added organic and inorganic materials in the treatment.

Treatment T_5 recorded higher activity at panicle initiation as well as at harvest. Urease activity is crucial in the transformation of urea, therefore, with the conjoint application of inorganic fertilizer (urea) and vermicomposted rice straw in T_5 its activity increased. As always, absolute control registered lowest urease activity. This may be due to the lack of substrates in T_1 (absolute control). Guan (1987) reported that more availability of nitrogen resource for soil microorganisms resulted in higher soil urease activity because of substrate availability. Urease activity is preferably higher in paddy soil with abundant organic matter and higher levels of total nitrogen content (Zeng Lu- Sheng *et al*., 2005). The lower urease activity in biochar amended plots compared to vermicompost applied plots might be due to the highly recalcitrant structure of biochar.

Urease activity increased upto panicle initiation followed by a decrease at harvest. Reduction in urease activity at harvest might be due to dry condition of soil and reduced root activity with the crop reaching late maturity stage.

5.3.4.3. Acid phosphatase activity

Acid phosphatase is contributed both by the plant roots as well as soil inhabiting microbes (Chhonkar *et al*., 2007) and it cleaves the phosphate from organic substrates and is involved in the phosphorus cycle in soil. The effects of treatments on acid phosphatase activity at different stages of crop were studied and are depicted in Figure 5.79.

The conjoint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) registered higher acid phosphatase activity at all stages. This might be due to the phosphorus status in T_5 contributed by inorganic fertilizer and vermicomposted rice straw. The higher total phosphorus content in vermicomposted rice straw compared to other organic amendments was evidenced from the characterization done in the present study. As expected, lowest enzyme activity was found in T_1 and this might be due to the lack of external inputs. Sarma *et al*. (2017) reported that the conjoint application of organic amendments and inorganic fertilizers significantly increased phosphatase activity than lone application of organic amendments and inorganic fertilizers. They also pointed out that among the organic amendments, vermicompost followed by FYM stimulated phosphatase activity at a higher rate than biochar.

Acid phosphatase activity followed an increasing trend upto panicle initiation and thereafter it decreased in all treatments. Decrease in acid phosphatase activity at harvest is mainly due to the dry soil condition that prevailed during harvest of rice and reduced root activity of rice at its later maturity stage. Aparna (2000) claimed that decrease in enzyme activity was mainly due to the lack of optimum conditions *viz*., availability of moisture, substrates and nutrients at harvest.

5.3.5. Effect of treatments on nutrient content in plant

5.3.5.1. Nitrogen

Treatments had a promising effect on nitrogen content in plant. At tillering, statistically higher nitrogen content was recorded in treatments T_5 as well as T_2, and they were on par. Soil receiving conjoint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) registered higher nitrogen at panicle initiation as well as at harvest (Figure 5.80). Higher nitrogen content in vermicomposted rice straw and inorganic fertilizer (urea) may enhanced the nitrogen status of soil and resulted in greater nitrogen in plant. Significant and positive correlation existed between soil-N and plant-N (0.890**). As expected, nitrogen content was lower in T_1 (absolute control) than that of other treatments. This might be due to the lack of any external inputs in these plots.

Nitrogen content was found to decrease in all treatments at harvest than that in previous stages of crop growth probably because of reduced nitrogen status of soil. Significant and positive correlation existed between soil-N and plant-N (0.890**). Geetha (2015) reported that lower nitrogen content at later stages of crop than that of previous stages may be because of lesser absorption at later stages.

5.3.5.2. Phosphorus

Treatment T_5 had higher phosphorus content followed by T_2. At tillering as well as at harvest of rice, phosphorus content in T_5 and T_2 were statistically on par. At all stages, absolute control recorded lower phosphorus and this may due the lack of any external organic and inorganic phosphorus sources in these plots.

With the advancement of crop growth, phosphorus content in plant decreased in all the treatments and this might be due to the reduced phosphorus status in soil at later stages of crop (Figure 5.81). The available phosphorus content in post-harvest soil and phosphorus content in plant at harvest are significantly and positively correlated (0.935**).

5.3.5.3. Potassium

The treatments imposed resulted in significant variation in potassium content of plant. The soil receiving combined application of soil test based nutrient recommendation and rice straw biochar (T_7) registered higher potassium content followed by soil receiving conjoint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5). The higher potassium in rice straw derived products *viz.*, rice straw biochar and vermicomposted rice straw as well as potassium present in the inorganic fertilizer (muriate of potash) might be the reasons for higher potassium in T_7 and T_5. As always, potassium content was lowest in absolute control due to the absence of external inputs in these plots. At harvest, potassium content was decreased in all treatments and this might be due to the lower potassium status in soil (Figure 5.82).

Correlation analysis revealed that potassium fractions had significant and positive correlation with plant potassium at tillering as well as panicle initiation. Similarly, available potassium of post- harvest soil had significant and positive correlation with potassium content of plant at harvest (0.865**).

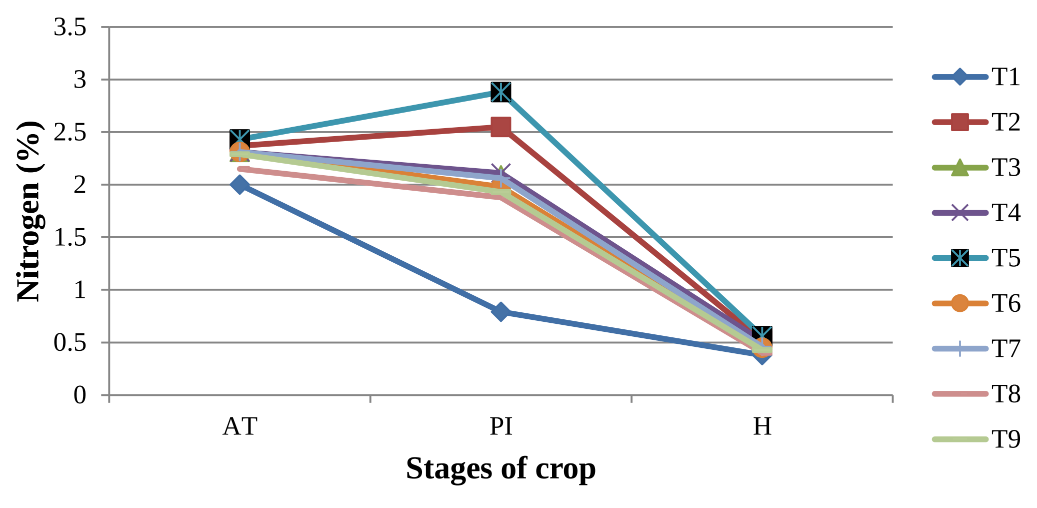


Fig.5.80: Changes in nitrogen content in plant at different stages of crop

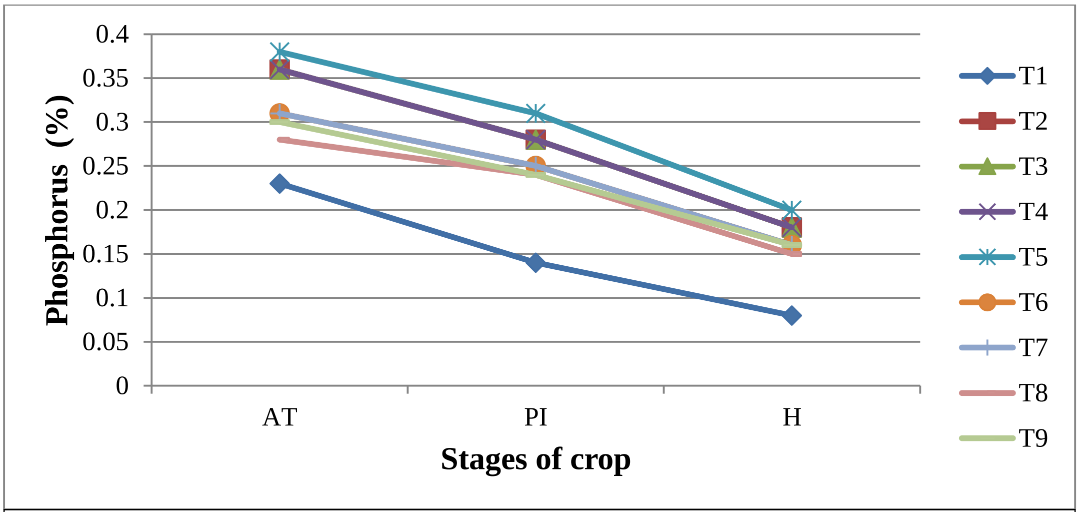


Fig.5.81: Changes in phosphorus content in plant at different stages of crop

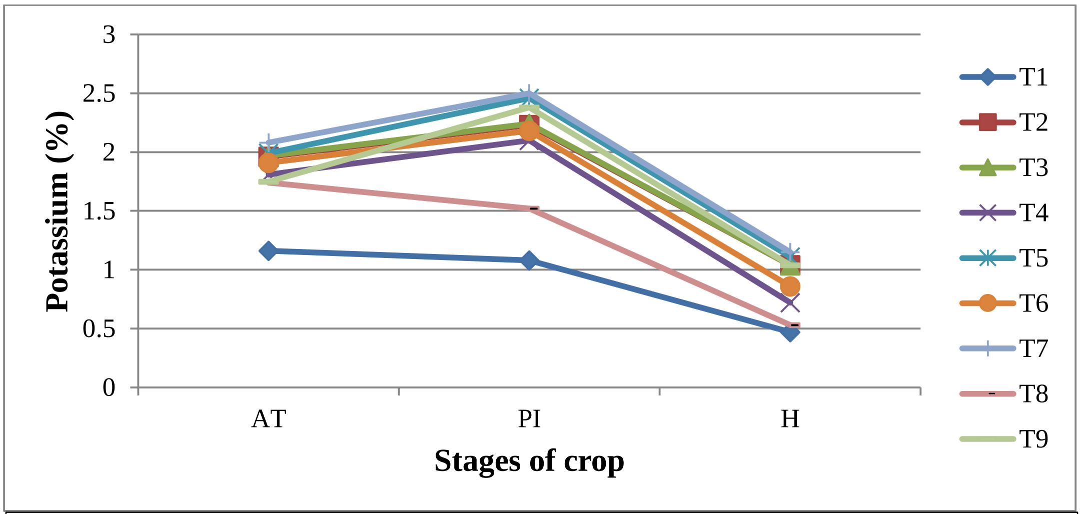


Fig.5.82: Changes in potassium content in plant at different stages of crop

5.3.5.4. Calcium

The calcium content in plant at different stages of crop *viz.*, at tillering, panicle initiation, and harvest were significantly influenced by the treatments imposed. Soil receiving conjoint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) registered significantly higher calcium content at all stages than other treatments. This might be due to the greater calcium content in T_5 from lime as well as vermicomposted rice straw. Absolute control recorded lowest calcium content and it could be attributed mainly by the lack of external inputs in these plots.

Calcium content in plant decreased at the harvest of rice in all treatments and it might be due to the depletion of calcium in soil by crop uptake (Figure 5.83). Available calcium in post-harvest soil had highly significant and positive correlation with calcium content in plant (0.962**).

5.3.5.5. Magnesium

At tillering stage, magnesium content was highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw). At panicle initiation and harvest magnesium content in T_5 and T_2 were higher and comparable. As expected, magnesium content was lowest in absolute control (Figure 5.84).

The magnesium content at harvest had highly significant and positive correlation with available magnesium of post-harvest soil (0.934**).

5.3.5.6. Sulphur

Application of treatments resulted in significant variation in sulphur content between treatments. At all sampling intervals *viz.*, at tillering, panicle initiation, and harvest T_5 recorded higher sulphur content and lowest by T_1.

With advancement of crop growth, sulphur content in plant followed a decrease in trend (Figure 5.85). This might be due to the reduced available sulphur fraction and total sulphur fraction in soil. Available sulphur in soil had significant and positive correlation with plant sulphur at tillering (0.891**), panicle initiation (0.862**), and harvest (0.807**).

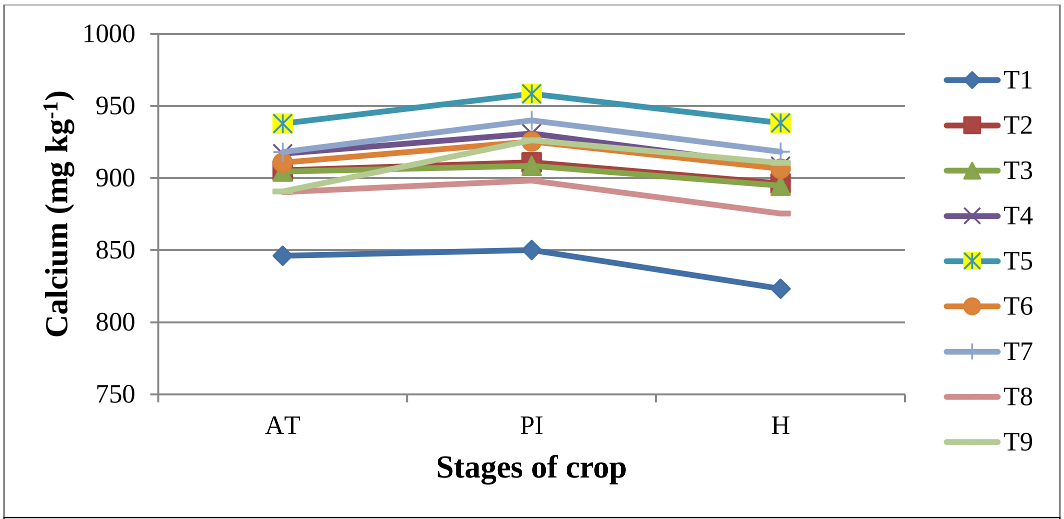


Fig.5.83: Changes in calcium content in plant at different stages of crop

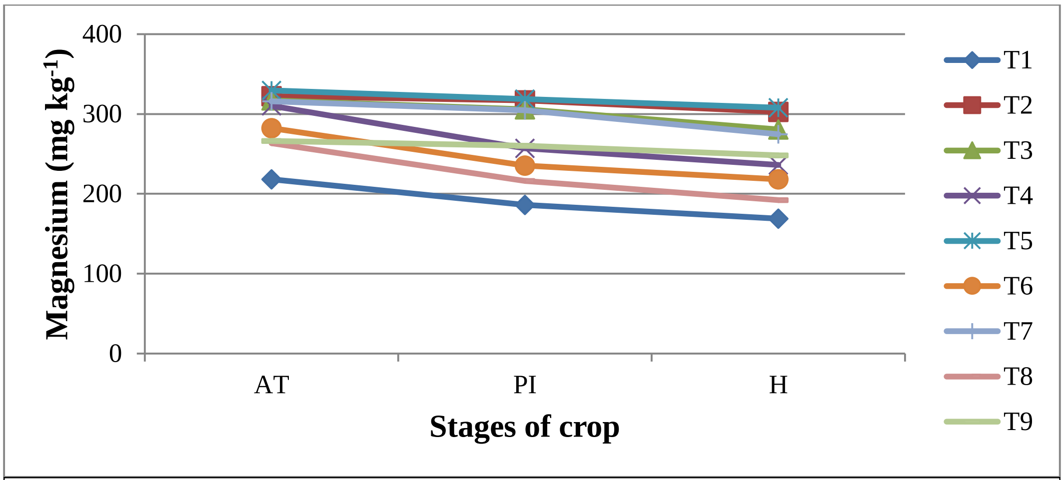


Fig.5.84: Changes in magnesium content in plant at different stages of crop

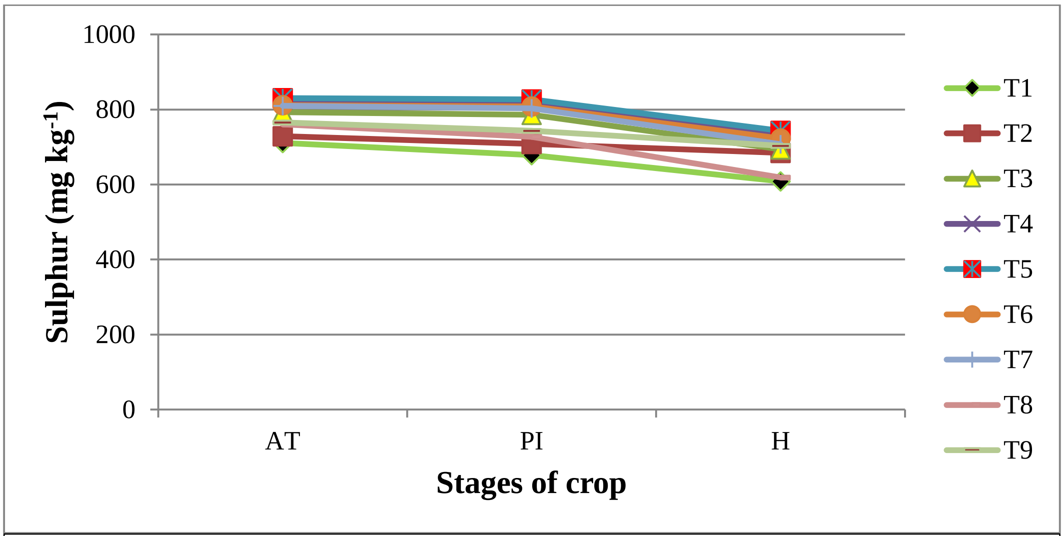


Fig.5.85: Changes in sulphur content in plant at different stages of crop

5.3.5.7. Iron

Soil receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) recorded higher iron content in plant at tillering, panicle initiation, and harvest and lowest was associated with absolute control.

With later stages of crop growth, iron content in plant followed a decrease in trend (Figure 5.86). The iron content in plant had highly significant and positive correlation with available iron content of soil (0.985**).

5.3.5.8. Manganese

Among the nine treatments, T_5 (soil test based nutrient recommendation + vermicomposted rice straw) registered higher manganese at all stages of sampling and lowest was noticed in absolute control.

The manganese content in plant decreased with crop growth (Figure 5.87). This might be due to the lower nitrogen status of soil and lesser absorption at later stages. The available manganese content in soil had significant and positive correlation with manganese content in plant (0.902**).

5.3.5.9. Copper

The copper content in plant was highest in treatments T_5 and lowest in $T_{1.}$ The content of copper was found reduced at harvest in comparison with that at tillering and panicle initiation stage (Figure 5.88). This might be due to lower copper status in soil. Coefficient of correlation between available copper in harvested soil and plant copper was significant and positive (0.834**).

5.3.5.10. Zinc

Treatments T_5 and T_2 registered statistically higher zinc at tillering and panicle initiation. At harvest, T_5 recorded higher zinc followed by T_2. The zinc content in plant followed a decrease in trend with crop growth (Figure 5.89). Zinc content in soil had significant and positive correlation with zinc in plant (0.940**).

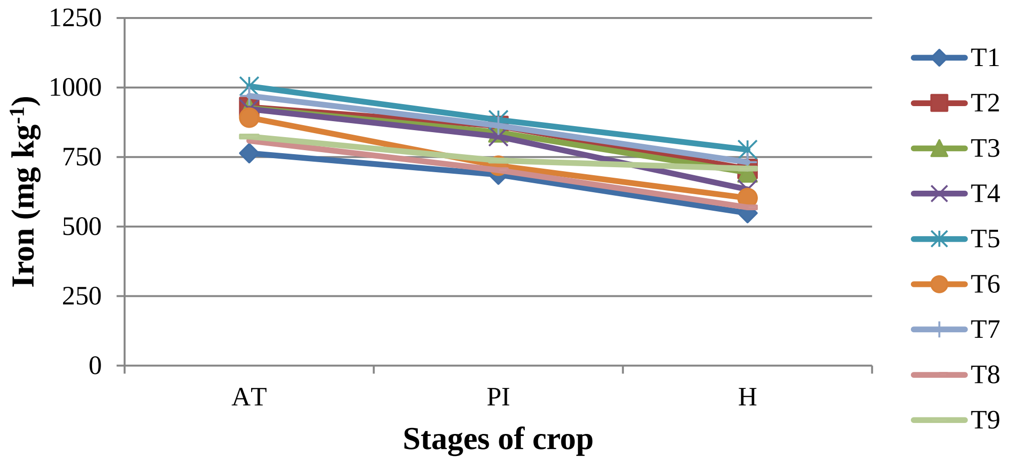


Fig.5.86: Changes in iron content in plant at different stages of crop

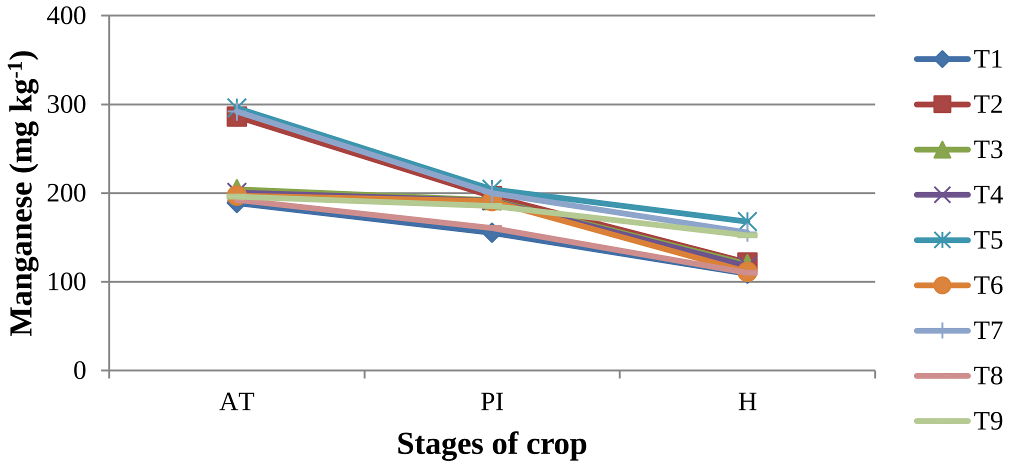


Fig.5.87: Changes in manganese content in plant at different stages of crop

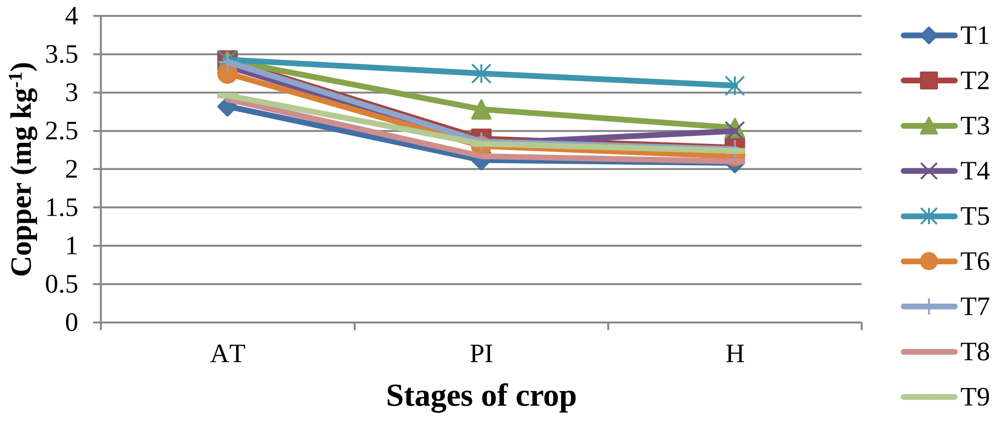


Fig.5.88: Changes in copper content in plant at different stages of crop

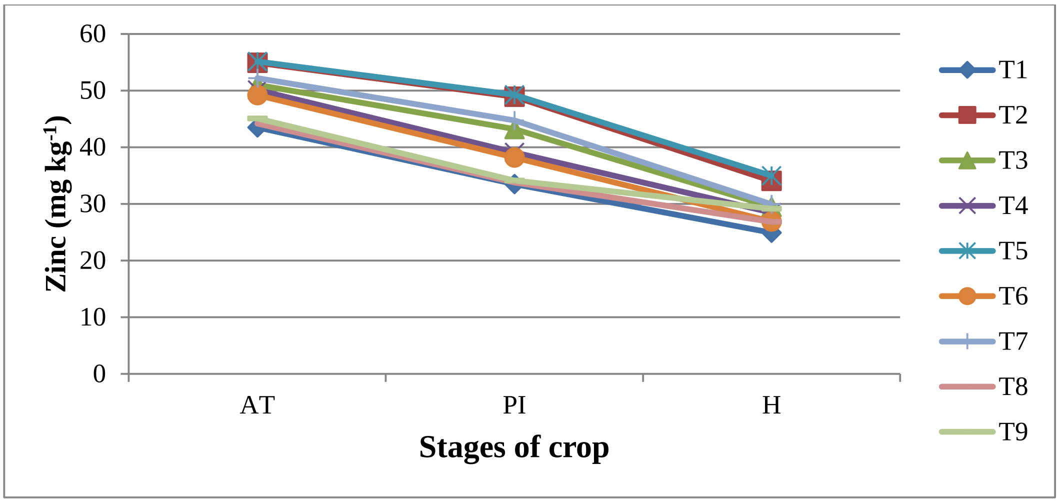


Fig.5.89: Changes in zinc content in plant at different stages of crop

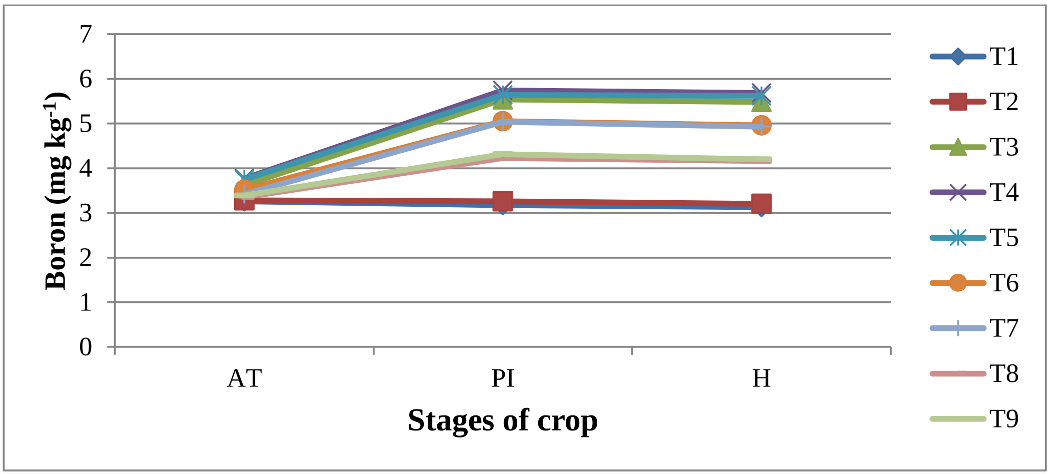


Fig.5.90: Changes in boron content in plant at different stages of crop

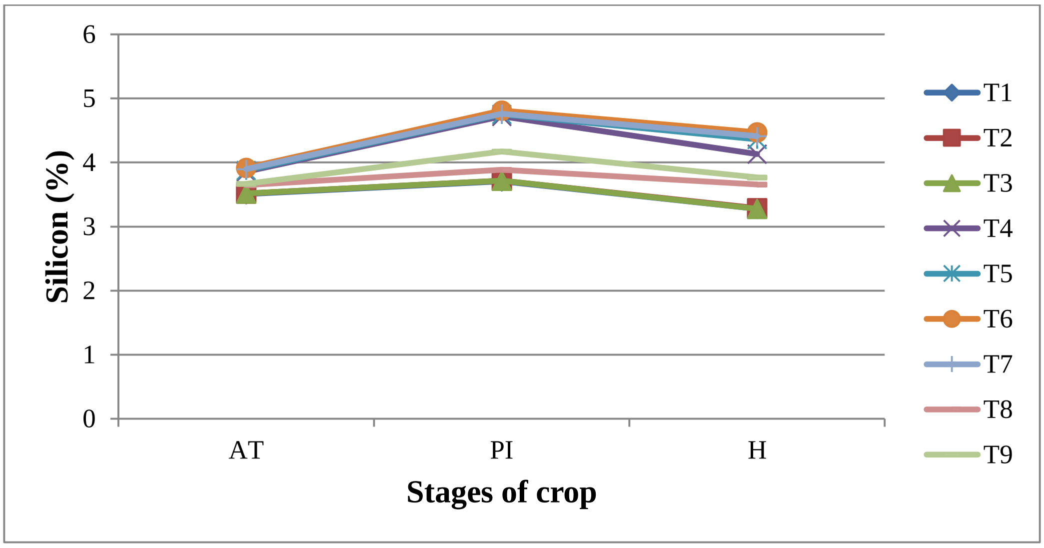


Fig.5.91: Changes in silicon content in plant at different stages of crop

5.3.5.11. Boron

Boron content in T_4 and T_5 were on par and higher than that of other treatments at tillering, panicle initiation and harvest (Figure 5.90). The boron content in plant increased at panicle initiation in all treatments except T_1 and T_2. This might be due to the application of borax as per soil test recommendation in treatments T_3 to T_9. The coefficient of correlation between boron in soil and plant at harvest was 0.982**.

5.3.5.12. Silicon

The silicon content was statistically highest in biochar amended treatments (T_6 and T_7) at tillering, panicle initiation and harvest (Figure 5.91). The lower silicon content was observed in T_1, T_2 and T_3 and they were statistically on par. This might be due to the lack of silicon sources in these plots. Silicon content in soil and plant at harvest had significant and positive correlation (0.776*). Silicon content in plant at tillering and panicle initiation was significantly and positively related with silicon fractions in soil *viz*., mobile-Si, adsorbed-Si, organic-Si, occluded-Si, and residual-Si.

5.3.6. Biometric observations

Biometric observations were recorded at tillering, panicle initiation and at harvest.

5.3.6.1. Plant height

The plant height recorded at different stages of rice is depicted in Figure 5.92. At all stages, plant height was significantly superior in T_5 and T_2 and they were statistically on par. Plant height was significantly lower in absolute control than that of other treatments and this might be due to the lower nutrient status in these plots which were deprived of external inputs.

5.3.6.2. Number of tillers per hill

The application of T_5 was on par with T_3, T_2, and T_4 in significantly increasing the number of tillers per hill at tillering. At panicle initiation stage, T_5 recorded significantly higher number of tillers per hill. At harvest, application of T_5 was on par with T_2 in producing the highest number of tillers per hill (Figure 5.93).

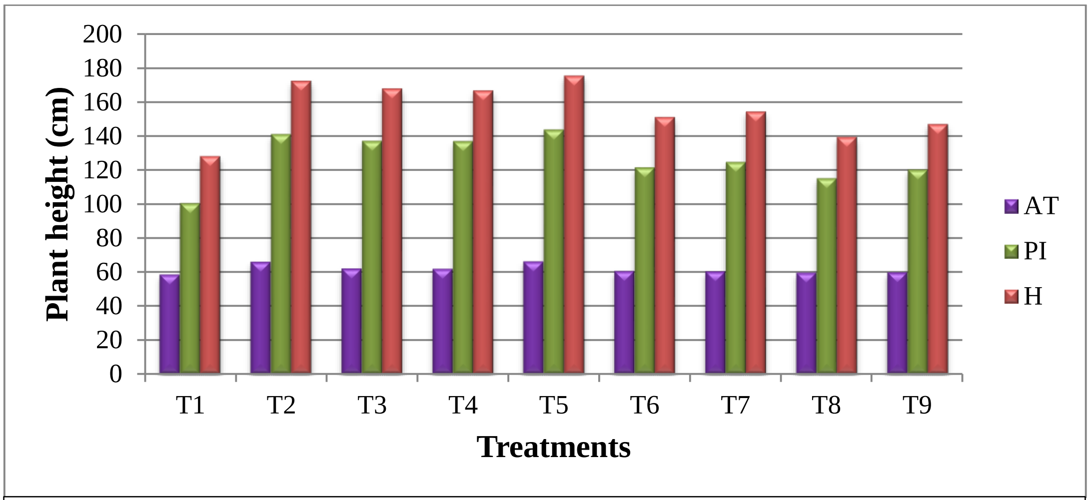


Fig.5.92: Effect of treatments on plant height

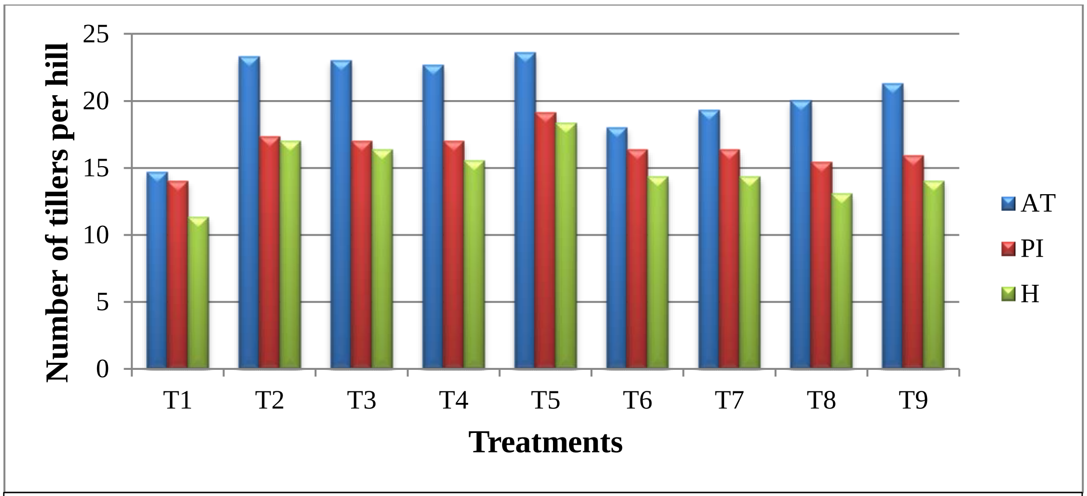


Fig.5.93: Effect of treatments on number of tillers per hill

5.3.6.3. Dry matter production

The collective application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) recorded significantly higher dry matter production at tillering, panicle initiation and at harvest (Figure 5.94). This might be due to the higher nutrient status in T_5 compared to other treatments. As expected, dry matter production was lowest in absolute control due to lower nutrient status in soil, where no external inputs were added during crop production.

5.3.6.4. Yield attributes

The joint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) recorded significantly higher number of panicles/m^2, spikelets/hill, filled grains/panicle (Figure 5.95-97). Thousand grain weight in T_5 and T_3 were significantly superior than that in other treatments (Figure 5.99). The chaff percentage was highest in absolute control and this might be due to the lower nutrient status (Figure 5.98).

5.3.6.5. Yield

The combined application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) was found to be the most effective treatment in recording the highest grain and straw yield (Figure 5.100).

Grain yield had highly significant and positive correlation with tillers/hill, plant height, panicles/m^2, spikelets/hill, filled grain/panicle, and thousand grain weight. Similarly, straw yield had highly significant and positive correlation with plant height and dry matter content.

5.3.7. Nutrient uptake

Nutrients are taken up by plant mainly as inorganic ions from soil solution. The rate of uptake depends primarily on the concentration of nutrients in the soil solution immediately adjacent to the root.

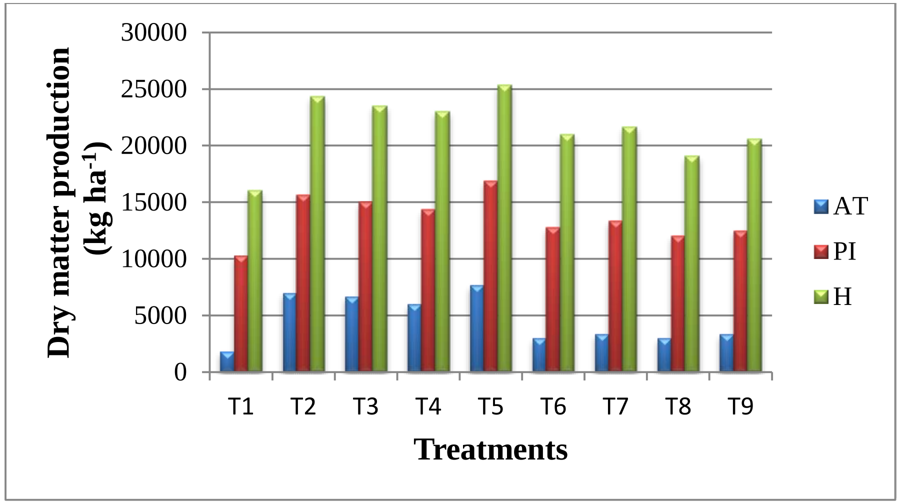


Fig.5.94: Effect of treatments on dry matter production

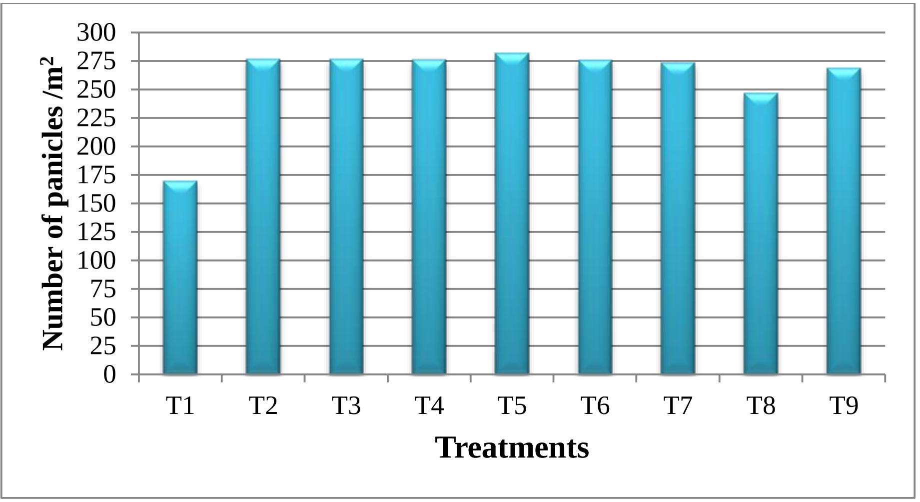


Fig.5.95: Effect of treatments on number of panicles /m^2

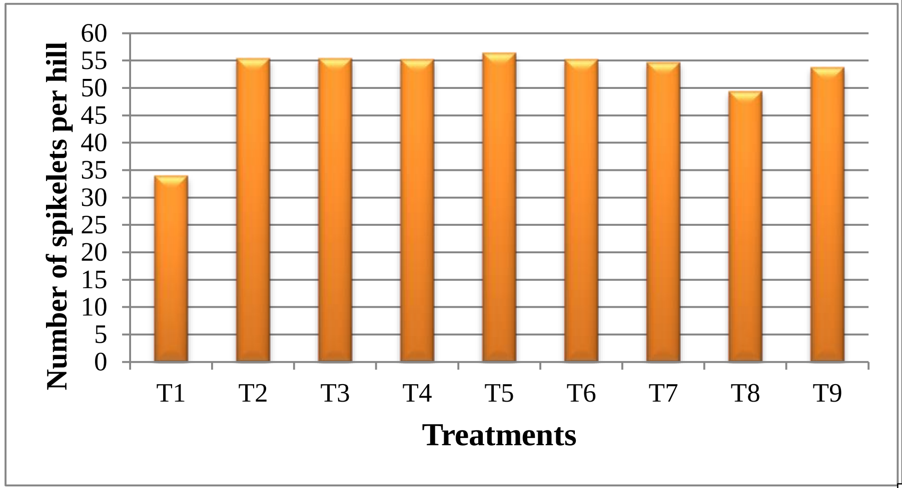


Fig.5.96: Effect of treatments on number of spikelets/ hill

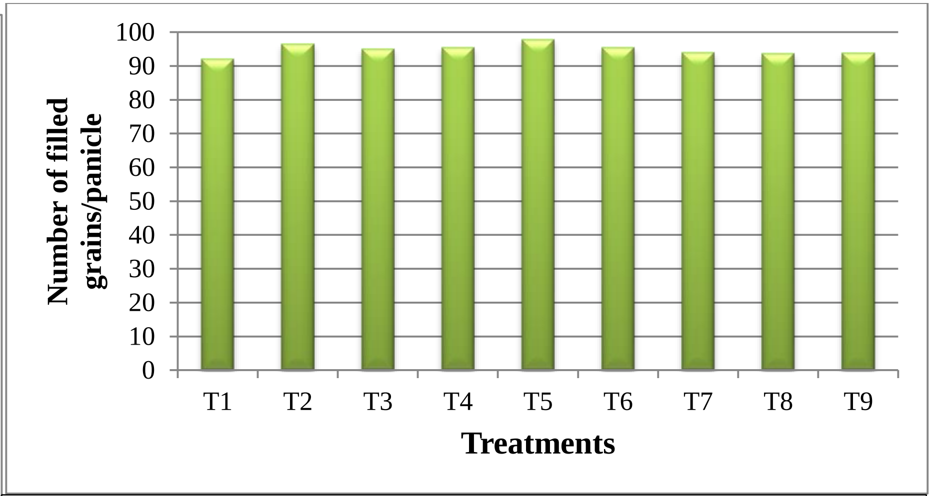


Fig.5.97: Effect of treatments on number of filled grains per panicle

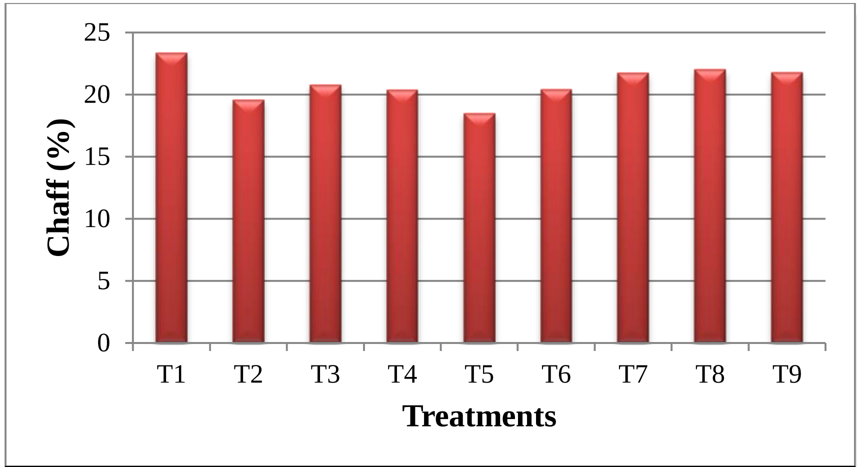


Fig.5.98: Effect of treatments on number of chaff percentage

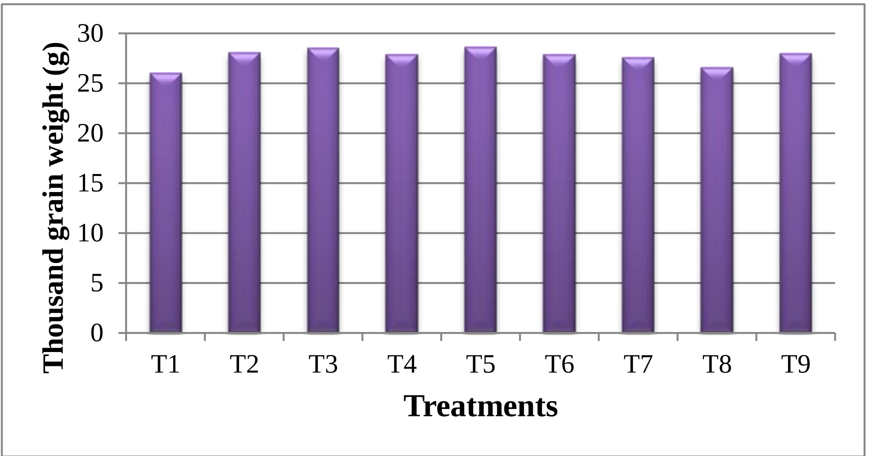


Fig.5.99: Effect of treatments on thousand grain weight

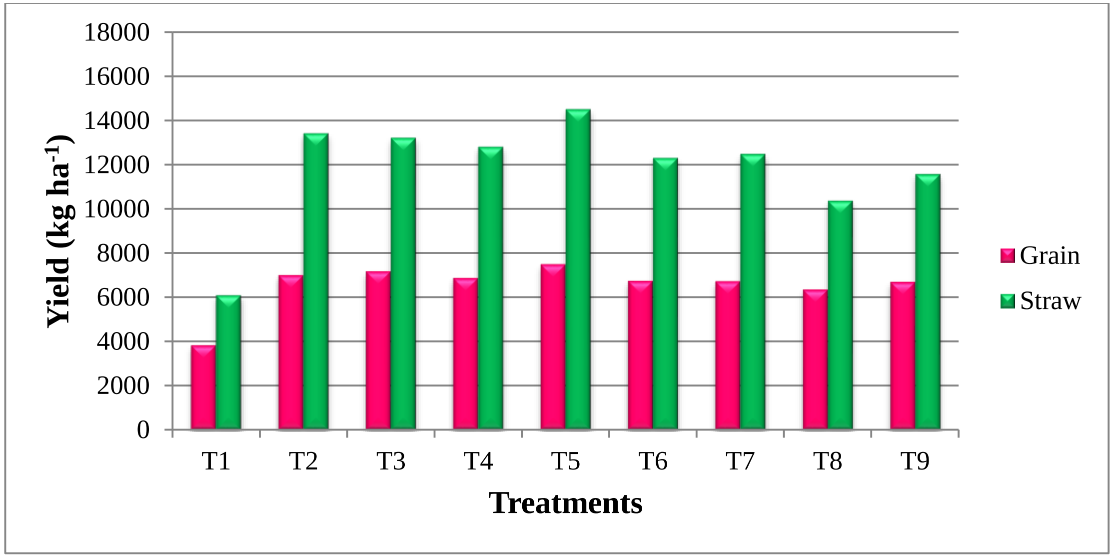


Fig.5.100: Effect of treatments on grain and straw yield

Nutrient uptake is related to the concentration of nutrient in plant as well as the dry matter production. During the initial stages of crop growth there is higher concentration of nutrients, where the nutrient supply exceeds dry matter production but at later stages of crop growth, dry matter production will be more than the nutrient supply.

The total uptake of N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B and Si in T_5 was significantly higher than that in other treatments. The uptake of N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B and Si in T_5 was 141.86 kg ha^{-1}, 50.67 kg ha^{-1}, 280.35 kg ha^{-1}, 23.77 kg ha^{-1}, 7.80 kg ha^{-1}, 18.83 kg ha^{-1}, 19.66 kg ha^{-1}, 4.25 kg ha^{-1}, 0.885 kg ha^{-1}, 0.075 kg ha^{-1}, 0.189 kg ha^{-1}, and 1104.52 kg ha^{-1} respectively. Significantly lowest nutrient uptake was observed in absolute control and this might be due to the lower nutrient status in these plots.

A perusal data on correlation analysis between chemical properties of post- harvest soil and nutrient uptake revealed that nutrient uptake had highly significant and positive correlation with available nutrients in soil. Similarly, organic carbon content of post-harvest soil had significant and positive correlation with crop uptake.

Significantly the highest nutrient uptake was observed in treatment that received conjoint application of soil test based nutrient recommendation and vermicomposted rice straw at 5t ha^{-1}(Figure 5.101-112). The nutrients present in the added chemical fertilizers and vermicomposted rice straw would have resulted in higher nutrient uptake. Vermicompost has tremendous potential to supply plant nutrients for sustainable crop production. Enhanced nutrient supply is the result of increased microbial activity in the intestine of earthworms which is subsequently excreted through earthworm gut as vermicompost.

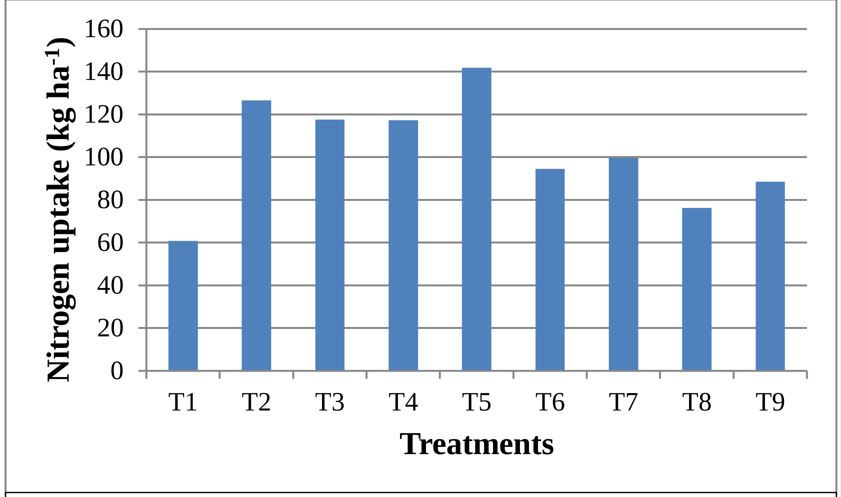


Fig.5.101: Effect of treatments on nitrogen uptake

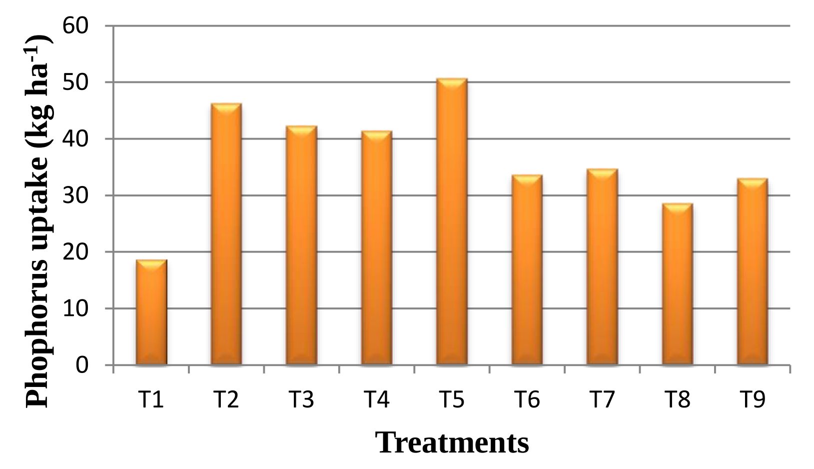


Fig.5.102: Effect of treatments on phosphorus uptake

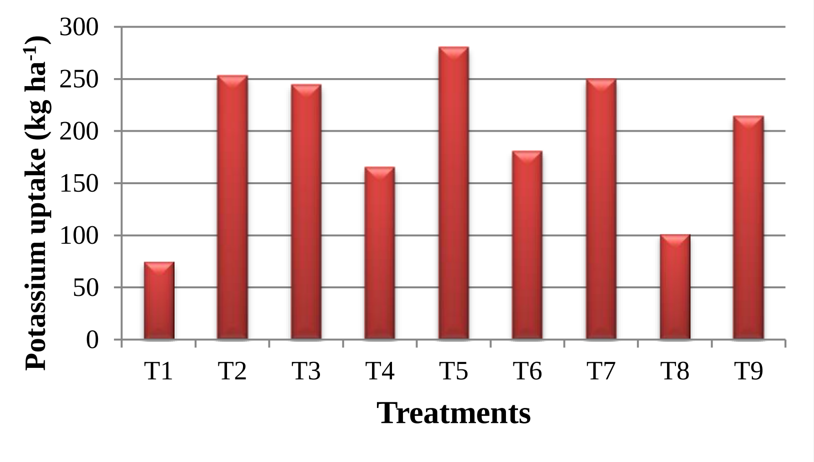


Fig.5.103: Effect of treatments on potassium uptake

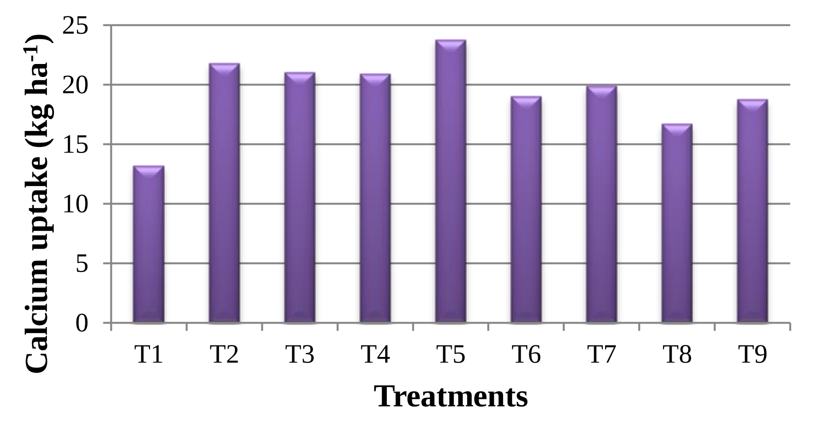


Fig.5.104: Effect of treatments on calcium uptake

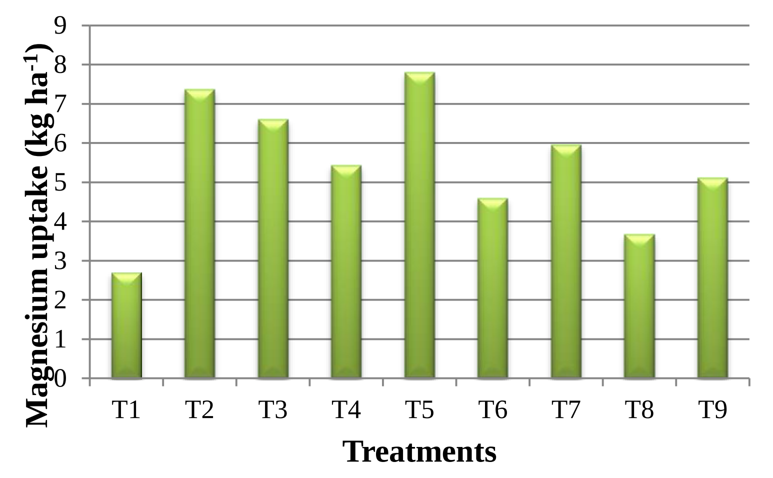


Fig.5.105: Effect of treatments on magnesium uptake

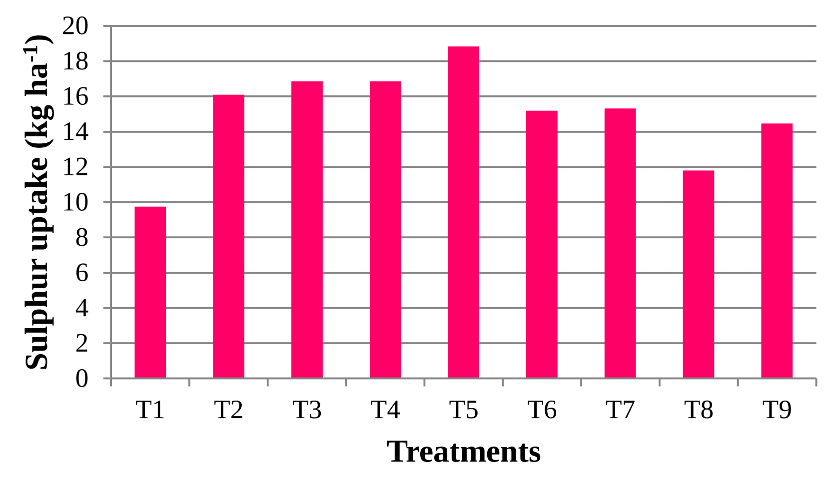


Fig.5.106: Effect of treatments on sulphur uptake

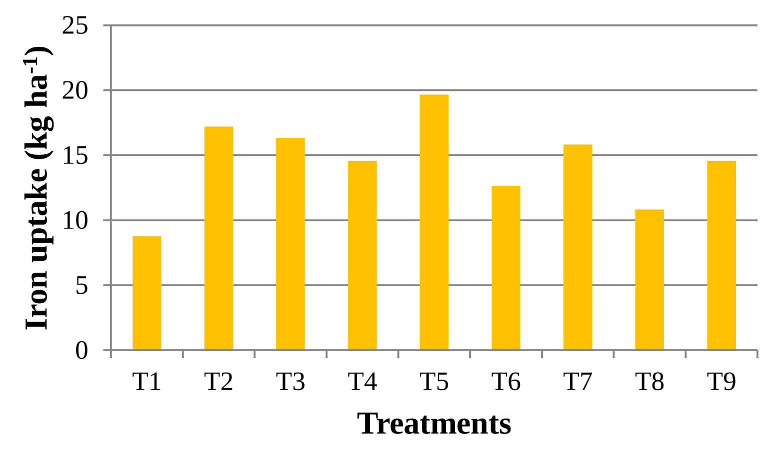


Fig.5.107: Effect of treatments on iron uptake

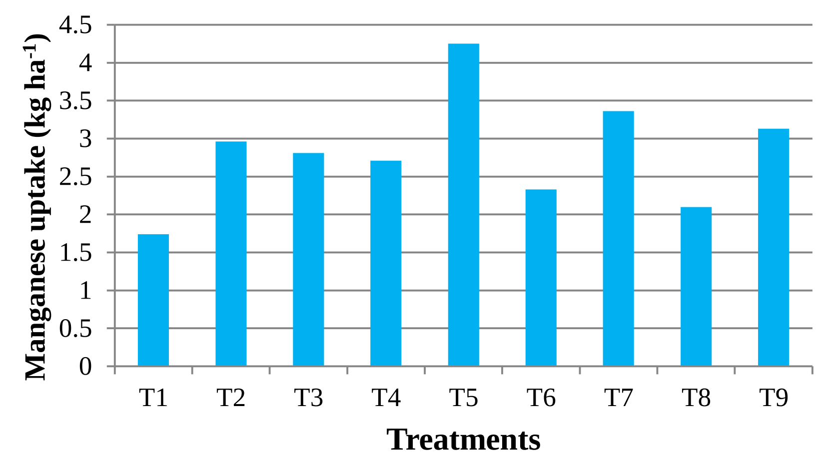


Fig.5.108: Effect of treatments on manganese uptake

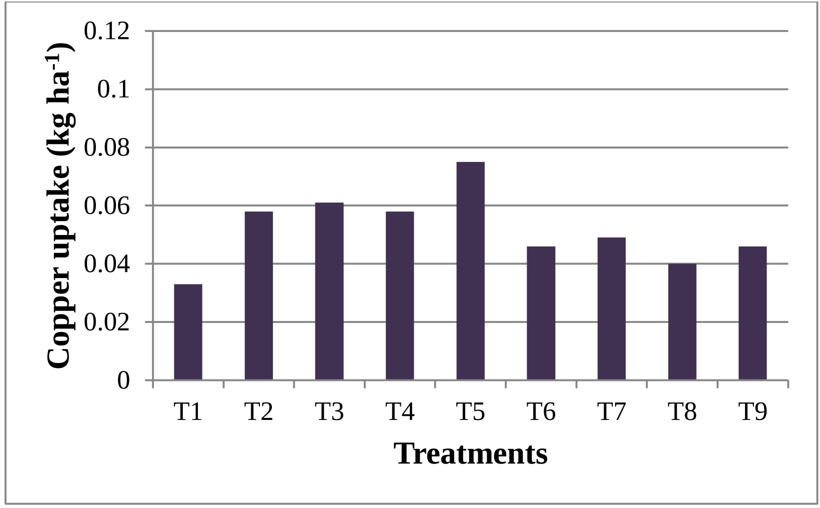


Fig.5.109: Effect of treatments on copper uptake

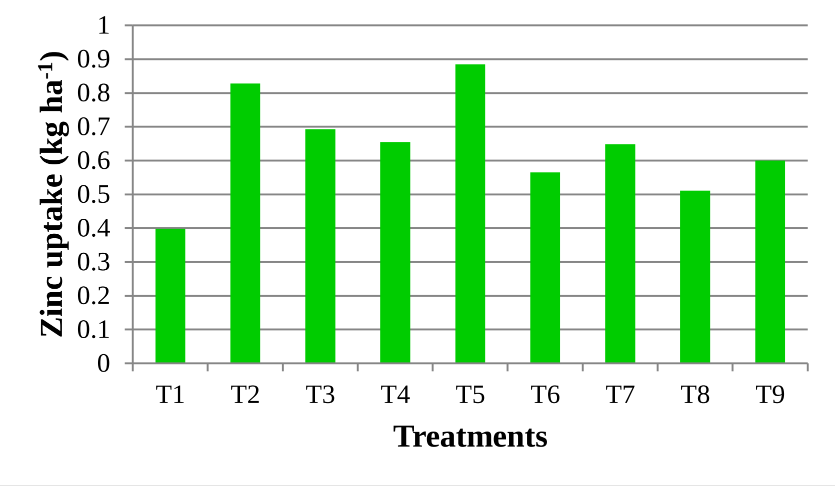


Fig.5.110: Effect of treatments on zinc uptake

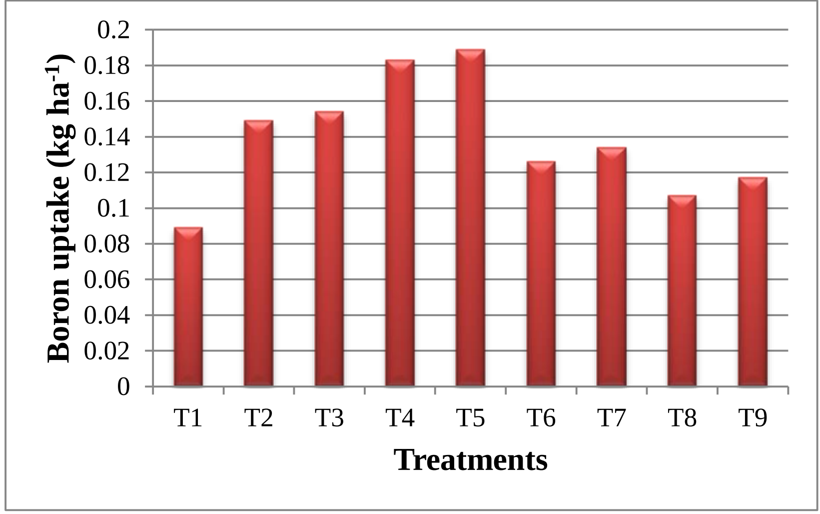


Fig.5.111: Effect of treatments on boron uptake

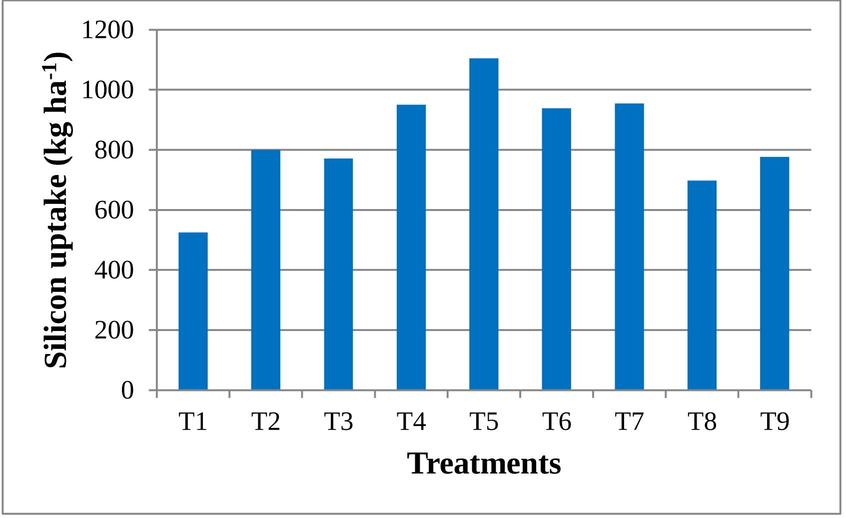


Fig.5.112: Effect of treatments on silicon uptake

SUMMARY

6. SUMMARY

The present study titled "Nutrient dynamics and crop productivity in lowland lateritic soil (AEU 10) under rice residue management practices" was carried out in three phases *viz.* 1. characterization of rice residues and their products (Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellanikkara) 2. an incubation experiment (Kerala Forest Research Institute, Peechi) 3. a field experiment (rice field, Agricultural Research Station, Mannuthy). The salient research findings emanated are summarized herewith.

6.1. CHARACTERIZATION OF RICE RESIDUES AND THEIR PRODUCTS

The vermicompost and biochar intended for the study were produced from the rice straw and husk using vermitechnology and pyrolysis in the vermi unit of Department of Soil Science and Agricultural Chemistry.

- ❖ The output or recovery from vermicomposting was more (74.38% for vermicomposted rice straw and 70.03 % for vermicomposted rice husk) than when the residues were converted into biochar through pyrolysis (19.86 % for rice straw biochar and 38.00 % for rice husk biochar).
- ❖ Among the rice residues, moisture content of straw was higher (7.24 %) compared to husk (6.03 %). Pyrolysis process reduced the moisture content of biochar, whereas vermicomposting resulted in an increase in moisture content.
- ❖ Higher moisture content was observed in vermicomposted rice straw (23.68 %) than vermicomposted rice husk (18.94 %).
- ❖ Among the produced biochar, rice husk biochar recorded highest moisture content (4.68 %) than rice straw biochar (3.62 %).
- ❖ Rice residues such as straw and husk, were yellow in colour whereas the resultant vermicompost from both the residues were brown in colour and that of biochar produced was black.
- ❖ No foul odour could be experienced from the residues and their products. Particle size determination following FCO specification revealed that 100 per cent of the composted materials and biochars passed through 4 mm IS sieve.
- ❖ Vermicomposting and pyrolysis reduced the bulk density of raw materials. Vermicomposted rice husk had comparatively lower bulk density (0.72 Mg m^{-3}) than

vermicomposted rice straw (0.78 Mg m^{-3}). Rice straw biochar showed comparatively higher bulk density (0.64 Mg m^{-3}) than rice husk biochar (0.59 Mg m^{-3}).

- Rice residues and their products were alkaline, with biochar exhibiting the highest level of alkalinity. The pH of biochar (9.24 for rice straw biochar and 9.20 for rice husk biochar) was comparatively higher than the initial residues (7.81 for straw and 7.24 for rice husk) as well as vermicompost (8.71 for vermicomposted rice straw and 7.97 for vermicomposted rice husk).
- The electrical conductivity increased both by vermicomposting and pyrolysis. However, electrical conductivity of biochar was lower than vermicomposts.
- Straw was comparatively superior to the husk in respect of C, N, K, Ca, Mg, Fe, Mn, Cu, and Zn.Whereas, husk was superior in P, S, B, Si, cellulose, and lignin.
- Vermicomposting helped to concentrate the nutrients *viz*., N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, B, and silicon and reduce the content of carbon, cellulose and lignin thereby narrowing down the C: N ratio.
- Conversion of residues into biochar helped to augment the nutrients *viz*., P, K, and Si in the final product, while carbon as well as other nutrients, cellulose, and lignin content were found to be decreased after pyrolysis. However, C: N ratio increased upon pyrolysis.
- The carbon content of residues and products followed the order: rice straw (36.45 %) > rice husk (35.22 %) > rice straw biochar (35.15 %) > rice husk biochar (34.86 %) > vermicomposted rice husk (31.75 %) > vermicomposted rice straw (18.25 %).
- The nitrogen content of the residues and products was in the order: vermicomposted rice straw (1.23 %) > vermicomposted rice husk (0.72 %) > rice straw (0.52%) > rice husk (0.41%) > rice straw biochar (0.40 %) > rice husk biochar (0.32 %).
- Phosphorus content of the residues and products obeyed the order: vermicomposted rice straw (0.34 %) > vermicomposted rice husk (0.26 %) > rice husk biochar (0.24 %) > rice straw biochar (0.22 %) > rice husk (0.21%) > rice straw (0.20 %).
- Potassium content of the residues and products catched the order: rice straw biochar (1.34 %) > vermicomposted rice straw (1.31 %) > rice straw (1.29 %) > rice husk biochar (0.30 %) > vermicomposted rice husk (0.27 %) > rice husk (0.26 %).
- The calcium content of the residues and their products was in the order: vermicomposted rice straw (582.45 mg kg^{-1}) > rice straw (548.32 mg kg^{-1}) > rice straw biochar (548.26 mg kg^{-1}) > vermicomposted rice husk (132.68 mg kg^{-1}) > rice husk (132.47 mg kg^{-1}) > rice husk biochar (131.06 mg kg^{-1}).

- Magnesium content of the rice residues and their products was in the order: vermicomposted rice straw (370.17 mg kg^{-1}) > rice straw (269.20 mg kg^{-1}) > rice straw biochar (260.02 mg kg^{-1}) > vermicomposted rice husk (130.01 mg kg^{-1}) > rice husk (127.14 mg kg^{-1}) > rice husk biochar (126.28 mg kg^{-1}).
- Sulphur content of the residues and their products complied the order: vermicomposted rice husk (542.76 mg kg^{-1}) > vermicomposted rice straw (540.00 mg kg^{-1}) > rice husk (536.83 mg kg^{-1}) > rice husk biochar (536.12 mg kg^{-1}) > rice straw (530.08 mg kg^{-1}) > rice straw biochar (528.98 mg kg^{-1}).
- The iron content of the residues and their products obeyed the order: vermicomposted rice straw (441.26 mg kg^{-1}) > rice straw (432.01 mg kg^{-1}) > rice straw biochar (429.75 mg kg^{-1}) > vermicomposted rice husk (159.34 mg kg^{-1}) > rice husk (152.62 mg kg^{-1}) > rice husk biochar (149.57 mg kg^{-1}).
- The rice residues and their products differed in their manganese content and it was in the order: vermicomposted rice straw (83.92 mg kg^{-1}) > rice straw (80.24 mg kg^{-1}) > rice straw biochar (78.53 mg kg^{-1}) > vermicomposted rice husk (42.17 mg kg^{-1}) > rice husk (38.14 mg kg^{-1}) > rice husk biochar (36.01 mg kg^{-1}).
- Zinc content of rice residues and their products followed the order: vermicomposted rice straw (24.01 mg kg^{-1}) > rice straw (23.26 mg kg^{-1}) > rice straw biochar (23.15 mg kg^{-1}) > vermicomposted rice husk (7.24 mg kg^{-1}) > rice husk (7.18 mg kg^{-1}) > rice husk biochar (7.15 mg kg^{-1}).
- The copper content of residues and their products obeyed the order: vermicomposted rice straw (2.46 mgkg^{-1})> rice straw (2.23 mgkg^{-1}) > rice straw biochar (2.01 mg kg^{-1}) > vermicomposted rice husk (1.48 mg kg^{-1}) > rice husk (1.26 mg kg^{-1}) > rice husk biochar (1.10 mg kg^{-1}).
- The boron content of the residues and their products obeyed the order: vermicomposted rice husk (4.31 mg kg^{-1}) > rice husk (4.28 mg kg^{-1}) > rice husk biochar (4.25 mg kg^{-1}) > vermicomposted rice straw (3.89 mg kg^{-1}) > rice straw (3.86 mg kg^{-1}) > rice straw biochar (3.84 mg kg^{-1}).
- Rice is a typical silicon accumulating plant, and vermicomposting and charring of rice residues helped to enhance the silicon content which adopted the order: rice husk biochar (13.87%)> rice straw biochar (10.21%)> vermicomposted rice straw (8.37 %) > vermicomposted rice husk (8.26 %) > rice husk (8.23 %) > rice straw (5.08 %).
- The cellulose content in rice residues and their products was in the order: rice husk (40.36 %) > rice straw (38.10 %) > vermicomposted rice husk (20.84 %) >

vermicomposted rice straw (12.26 %) > rice husk biochar (4.06 %) > rice straw biochar (2.81 %).

- Lignin content of rice residues and their products catched the order: rice husk (27.82%) > vermicomposted rice husk (21.75 %) > rice straw (13.26) > rice husk biochar (13.06%) > vermicomposted rice straw (6.84%) > rice straw biochar (4.74%).
- Lignin and cellulose content decreased after vermicomposting and charring. The extent of reduction in lignin was lower compared to cellulose in both vermicompost and biochar.
- The extent of reduction in cellulose was in the order: Rice straw biochar (92.62 %) > rice husk biochar (89.94 %) > vermicomposted rice straw (67.82 %) >vermicomposted rice husk (48.36 %).
- The reduction in lignin content obeyed the order: rice straw biochar (64.25 %) > rice husk biochar (53.05 %) > vermicomposted rice straw (48.42 %) > vermicomposted rice husk (21.82 %).
- Ratio of C to N is an index of decomposition and microbial mineralization. The C: N ratio of straw and husk was 71.20 and 86.01 in the present study.
- Vermicomposting reduced the C: N ratio of residues (14.83 for vermicomposted rice straw and 44.09 for vermicomposted rice husk).
- The C: N ratio of rice husk biochar (108.94) was higher than that of rice straw biochar (87.88).
- Scanning electron microscopic image was made use of for understanding the surface morphology of rice residues and their products. The salient findings were as follows
    - ✓ The SEM micrographs of straw and husk exhibited a complex morphology with cell wall composition.
    - ✓ SEM micrograph of vermicomposted rice straw showed highly fragmented, disaggregated and porous structure which could not be visualised in vermicomposted rice husk, may be because the technology was more suited to decomposing rice straw than its husk.
    - ✓ The SEM analysis showed that the structure of biochar was porous, fragmented and heterogeneous. The particles gave a broken or distorted appearance thus resembling the plant structure.

- The FT-IR technique is an important tool to identify the characteristic functional groups. The structure of rice residues and their products were analysed using FT-IR and the findings were as follows

  - ✓ Each peak in FT-IR is assigned with corresponding functional groups and it clearly explained the presence of C, H, O, N, and Si in the residues and products.
  - ✓ Silicon is a major component in the chemical structure of rice material, and is illustrated by Si-O-Si and Si-H bond in FT-IR spectra of residues and their products *viz*., vermicompost and biochar.
  - ✓ Vermicompost had significant level of nitrogen rich compounds and low level of aliphatic or aromatic carbon compounds compared to the residue and biochar, as confirmed by the FT-IR analysis.
  - ✓ The complete disappearance of O-H/N-H stretching (>3000 cm^{-1}) and almost disappearance of aliphatic C-H stretching (3000-2500 cm^{-1}) was noted in the spectrum of biochar. While, peaks arising from the aromatic stretching became more apparent resulting in high C: N ratio of biochar.

6.2. INCUBATION EXPERIMENT

Incubation experiment for studying kinetics of carbon mineralization was conducted at Kerala Forest Research Institute, Peechi for 110 days simulating the crop duration. Lateritic soil collected from the rice field of Agricultural Research Station, Mannuthy was added with rice residues and their products and kept at 15, 25, 35 and 45 ºC, and CO_2 evolution was determined at frequent intervals till 110 days and the data were used for the carbon mineralization study. Dehydrogenase enzyme assay, enumeration of microbial population, and fractions of carbon were also undertaken at the end of incubation.

- The amount of CO_2–C mineralized during incubation increased with increasing temperature in all the treatments.
- Vermicomposted rice straw treated soils registered higher mineralizable carbon at 15, 25, 35 and 45 ºC registering 40.61, 53.20, 79.79, and 104.61 mg CO_2-C per 100g soil respectively.

- Among the rice residues, carbon mineralization was lowest in rice husk treated soils than straw. Among the rice residue products, carbon mineralization was lowest in biochar (RHB and RSB) treated soils than vermicompost (VRS and VRH).
- Rate of decomposition reaction decreased with increase in temperature indicating the exhaustion of substrates available for microbial decomposition.
- Application of organic amendments increased activation energy than the inorganic fertilizer treated soils. The more the activation energy, more is the thermal stability.
- The highest activation energy was found in rice husk biochar amended soil (12.79 kJ mol^{-1}) followed by rice straw biochar added soil (12.71 kJ mol^{-1}).
- Q_{10} values represent the temperature dependency of the reaction. The results showed that all treatments had Q_{10} values less than one due to exhaustion of substrates and increased recalcitrant nature of substrates at higher temperatures.
- After 110 days of incubation at four temperatures, dehydrogenase activity was lowest at 45ºC with a mean value of 21.47 µg TPF $g^{-1}day^{-1}$.
- Soils treated with vermicomposted rice straw kept at 15 ºC registered the highest dehydrogenase activity (31.46 µg TPF $g^{-1}day^{-1}$).
- After 110 days of incubation, microbial population (bacteria, actinomycetes, and fungi) was found to decrease.
- The population of bacteria was statistically highest in soils treated with vermicomposted rice straw kept at 15, 25, and 35 ºC compared to that at 45 ºC.
- The population of actinomycetes followed a decreasing trend with increase in temperature with lowest mean value in 45 ºC (4.64 $x10^{3}$ cfu g^{-1}soil) and highest in 15 ºC (6.22 $x10^{3}$ cfu g^{-1}soil).
- Drastic reduction in fungal population was noted in those soils kept at 35 ºC and 45 ºC.
- Comparatively, higher microbial population was registered in soils treated with vermicomposted rice straw.
- The water soluble carbon was found to be increased with rise in temperature and statistically higher mean value was noted in soils treated at 45 ºC (109.36 $mgkg^{-1}$).
- Soils treated with vermicomposted rice straw exhibited highest WSC with a mean value 116.26$mgkg^{-1}$.
- Vermicompost added soil registered higher HWEC with a mean value 461.09 $mgkg^{-1}$. Among the different temperatures studied, soils kept at 45 ºC recorded significantly

higher HWEC (455.90 mg kg^{-1}) in comparison to soils kept at 15 ºC that recorded the lowest (446.67 mg kg^{-1}).

- Soils treated with vermicomposted rice straw recorded highest MBC with a mean value 132.44 mg kg^{-1}.
- Temperature had an adverse effect on MBC and it was highest in soils treated at 15 ºC (116.46 mg kg^{-1}) and lowest at 45 ºC with a mean value of 106.44 mg kg^{-1}.
- The highest POXC was recorded in vermicomposted rice straw amended soils (1390.60 mg kg^{-1}).
- The highest POXC was noted at 15 ºC (1340.80 mg kg^{-1}) and lowest at 45 ºC (1065.56 mg kg^{-1}).
- Total carbon was found to be lowest in soils treated at 45ºC with a mean value of 1.03 per cent.
- Biochar amended soils (S_6 and S_7) recorded higher total carbon with a mean value of 1.14 per cent.

6.3. FIELD EXPERIMENT

Field experiment was carried out to evaluate the efficacy of rice residues and their products in lowland rice. The soil and plant samples were collected at different stages of crop growth to analyse the effect of treatments on soil properties, fractions of nutrients, nutrient content in plant, yield and yield attributes of rice.

Physical and chemical properties of post-harvest soil

- The Eh showed a reduction over the period after transplanting in all the treatments except at fourth week where the value revealed an increment.
- The application of residues and its products had profound influence in lowering redox potential.
- The soil pH followed a decreasing trend. Whereas, there was a slight increment in soil pH after four weeks of transplanting in all the treatments except T_1 (absolute control).

- The alkaline nature of rice residues and their products resulted in higher pH of experimental soil.

- The biochar amended treatments showed a higher soil pH throughout the period of crop indicating the alkaline nature and liming effect brought about by biochar.
- The application of various treatments had profound influence in altering physical properties of post-harvest soil *viz*., lowering soil bulk density, increasing porosity, MWD, and water holding capacity.
- The lowest bulk density was observed in T_6 and T_7 (biochar amended soils) with a value 1.28 Mgm^{-3}.
- Porosity of soils varied from 41.63 to 45.06 per cent, with lowest in absolute control and highest in biochar amended soils.
- Mean weight diameter (MWD) varied significantly among the treatments and highest MWD was observed in T_6 (1.40mm) which was on par with T_7 (1.37mm) and T_5 (1.36mm).
- The application of soil test based nutrients along with rice husk biochar (T_6) resulted in 45.28 per cent WHC and it was on par with T_7 (soil test based nutrient recommendation + rice straw biochar) having 44.85 per cent WHC.
- Soil amended with rice residues and their products such as vermicompost and biochar had an effect in increasing the carbon content of post- harvest soil.
- Application of vermicomposted rice straw along with soil test based nutrient recommendation resulted in an increase in nitrogen content of the soil (364.68kg ha^{-1}).
- Higher phosphorus content was noticed in plots that received in plots added with soil test based nutrient recommendation and vermicomposted rice straw at 5 t ha^{-1}(24.86 kg ha^{-1}).
- Significant increase in potassium content was observed after the combined application of soil test based nutrient recommendation and rice straw biochar at 5 t ha^{-1} (326.23 kg ha^{-1}).
- Among the treatments, T_5 (soil test based nutrient recommendation + vermicomposted rice straw at 5 t ha^{-1}) registered higher calcium (120.34 mg kg^{-1}) and magnesium (27.17 mg kg^{-1}) content.
- Significantly higher sulphur content (4.85 mg kg^{-1}) was noted in T_5 receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw at 5t ha^{-1}.

- Regarding micronutrients, the content of iron, manganese, zinc, and that of beneficial element silicon were found to be highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw at 5 t ha^{-1}).

Fractionation

Fractions of carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, and silicon were analysed at three stages of field experiment *viz*., before planting, at tillering, and at panicle initiation.

1. Carbon

- Water soluble carbon (WSC), hot water extractable carbon (HWEC), microbial biomass carbon (MBC), permanganate oxidizable carbon (POXC), and total carbon constituted the various fraction of carbon analysed. Of the different fractions, POXC contributed largely to total carbon followed by HWEC, MBC, and WSC.
- Soils receiving combined application of soil test based nutrient recommendation and vermicomposted rice straw at 5 t ha^{-1} recorded the highest WSC at all the stages.
- Among the different stages, WSC was highest at panicle initiation followed by tillering stage of rice.
- Treatment T_5 (soil test based nutrient recommendation + vermicomposted rice straw at 5 t ha^{-1}) registered the highest HWEC.
- The HWEC was found to decrease with advancement of crop growth.
- The MBC was highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw at 5 t ha^{-1}) and lowest in T_1 (absolute control) at all the stages. Another noticeable feature was the increased MBC at panicle initiation than at tillering and before planting.
- At all the stages, plots that received combined application of soil test based nutrient recommendation and vermicomposted rice straw at 5 t ha^{-1} (T_5) registered higher POXC and lowest values were associated absolute control (T_1).
- The content of POXC showed a decrease in value with the advancement of crop growth.
- The treatment, soil test based nutrient recommendation and biochar at 5 t ha^{-1} (T_6 and T_7) recorded significantly higher value of total carbon.

- Total carbon decreased at tillering and panicle initiation than the values obtained before planting.

2. Nitrogen

- The treatments, soil test based nutrient recommendation along with rice straw biochar, rice husk biochar, vermicomposted rice straw were comparable in terms of total hydrolysable nitrogen (THN) in registering higher values of 2296.35 mg kg^{-1}, 2285.10 mg kg^{-1}, and 2274.84 mg kg^{-1} respectively before planting of rice.
- At tillering stage, statistically higher THN was found in soil test based nutrient recommendation along with biochar treatments (T_6 and T_7). At panicle initiation stage, T_7 receiving combined application of soil test based nutrient recommendation and rice straw biochar recorded higher THN (2168.06 mg kg^{-1}).
- With advancement of crop growth, THN decreased irrespective of the treatments.
- Amino acid nitrogen (AAN) was highest in plots receiving soil test based nutrient recommendation and vermicomposted rice straw at all stages.
- With the advancement of crop growth AAN was found to decrease.
- Ammoniacal nitrogen fraction at panicle initiation was higher than that at tillering and statistically higher content was recorded in soil test based nutrient recommendation+ vermicomposted rice straw (54.81 mg kg^{-1}).
- The nitrate nitrogen fraction was higher in plots receiving combined application of soil test based nutrient recommendation+ vermicomposted rice straw at all the stages studied and values are 38.16 mg kg^{-1} before planting, 32.14 mg kg^{-1} at tillering, and 30.08 mg kg^{-1} at panicle initiation.
- With the advancement of crop growth, the content of nitrate nitrogen was found to decrease.

3. Phosphorus

- Organic-P was dominant in all the treatments than inorganic –P fractions. Among the inorganic fractions, Fe-P was dominant followed by sesquioxide occluded-P.
- The major fractions which contributed to available phosphorus in soil under submerged condition were Fe-P, Al-P, and sesquioxide occluded-P. The decrease in the above mentioned fractions were counterpoised by the corresponding increase in Ca-P with the advancement of crop growth.

- Soluble-P was increased at tillering followed by a decrease at panicle initiation in all the treatments except absolute control in which the soluble-P was found to show a decrease at tillering and panicle initiation stages of rice.
- Aluminium bound phosphorus was highest in plots receiving joint application of soil test based nutrient recommendation+ vermicomposted rice straw.
- The dominant inorganic-P fraction Fe-P was 141.81 mg kg^{-1} before planting, 140.52 mg kg^{-1} at tillering, and 138.86 mg kg^{-1} at panicle initiation stage in plots receiving joint application of soil test based nutrient recommendation+ vermicomposted rice straw.
- With advancement of crop growth, sesquioxide occluded-P was found to be decreased and it was highest in biochar amended plots.
- At tillering, treatments T_5 (37.81 mg kg^{-1}) and T_7 (37.00 mg kg^{-1}) are statistically superior in their Ca-P than that in other treatments.
- Before planting as well as at tillering, organic-P fraction was statistically highest in treatments T_7 and T_6. At panicle initiation, T_7 registered highest organic-P fraction.
- Organic-P was found to be decreased at tillering as well as panicle initiation compared to the fraction before planting.

4. Potassium

- The water soluble-K and exchangeable-K was highest in T_7 (soil test based nutrient recommendation+ rice straw biochar 5t ha^{-1}) at all the stages.
- Exchangeable-K was more than the water soluble -K.
- With advancement of crop growth, potassium fractions

5. Calcium

- Exchangeable calcium was more than the water soluble calcium
- The treatment soil test based nutrient recommendation + vermicomposted rice straw at 5t ha^{-1}registered higher water soluble-Ca and exchangeable-Ca at all stages.
- Fractions of calcium increased with crop growth in all the treatments except T_1, where exchangeable -Ca decreased.

6. Magnesium

- Soil test based nutrient recommendation+ vermicomposted rice straw at 5t ha^{-1} registered higher magnesium fractions at all stages.

- Fractions of magnesium increased with crop growth in all the treatments except in T_1, where exchangeable- Mg decreased.

7. Sulphur

- Organic-S fraction was dominant in soil than the available-S.
- The available-S was found to decrease at panicle initiation stage compared to tillering stage.
- Organic sulphur got increased at tillering in all the treatments except T_1.

8. Silicon

- The results of silicon fractionation showed amorphous-Si as the dominant fraction in soil followed by residual-Si, organic-Si, occluded-Si, and mobile-Si, with adsorbed-Si as remaining as the least dominant fraction of silicon in soil.
- Comparatively higher silicon fractions were obtained in soils treated with soil test based nutrient recommendation + biochar.
- Application of treatments could not produce any significant difference in amorphous-Si.
- All silicon fractions were found to decrease with crop growth except mobile-Si.

Enzyme activity

1. Dehydrogenase activity

- Application of organic amendments significantly enhanced dehydrogenase activity.
- At tillering, panicle initiation and harvest, soil test based nutrient recommendation+ vermicomposted rice straw at 5 t ha^{-1} recorded highest dehydrogenase activity.
- Dehydrogenase activity was found to increase upto panicle initiation followed by a decrease at harvest.

2. Urease activity

- Treatment T_5 recorded higher activity at panicle initiation as well as at harvest.
- Urease activity increased upto panicle initiation followed by a decrease at harvest.

3. Acid phosphatase activity

- The conjoint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) registered higher acid phosphatase activity at all stages.

- Acid phosphatase activity followed an increasing trend upto panicle initiation and thereafter it decreased in all treatments.

Nutrient content in plant

- Soil receiving joint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) registered higher nitrogen at panicle initiation as well as at harvest.
- Nitrogen content was found to decrease in all treatments at harvest than that in previous stages of crop growth.
- Treatment T_5 had higher phosphorus content. With the advancement of crop growth, phosphorus content in plant decreased in all the treatments.
- The soil receiving combined application of soil test based nutrient recommendation and rice straw biochar (T_7) registered higher potassium content followed by soil receiving conjoint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5).
- At harvest, potassium content revealed a decrease in all treatments.
- Soils receiving conjoint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) registered significantly higher calcium content at all stages than other treatments.
- Calcium content in plant decreased at the harvest of rice in all treatments.
- At tillering stage, magnesium content was highest in T_5 (soil test based nutrient recommendation + vermicomposted rice straw).
- At all sampling intervals *viz*., at tillering, panicle initiation, and harvest T_5 recorded the highest sulphur content and T_1 the lowest.
- With advancement of crop growth, sulphur content in plant followed a decrease in trend.
- Soil receiving conjoint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) registered higher micronutrient status.
- The silicon content was statistically highest in biochar amended treatments (T_6 and T_7) at tillering, panicle initiation and harvest.
- Nutrient content in plant had significant and positive correlation with nutrients in soil.

Plant characters

- Plant height and dry matter production was highest in soil test based nutrient recommendation + vermicomposted rice straw (T_5).
- The joint application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) recorded significantly higher number of panicles/m^2, spikelets/hill, filled grains/panicle.
- The combined application of soil test based nutrient recommendation and vermicomposted rice straw (T_5) was found to be the most effective treatment in recording the highest grain (7490 kg ha^{-1}) and straw yield (14510 kg ha^{-1}).

- Grain yield had highly significant and positive correlation with tillers/hill, plant height, panicles/m^2, spikelets/hill, filled grain/panicle, and thousand grain weight. Similarly, straw yield had highly significant and positive correlation with plant height and dry matter content.

- The uptake of N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B and Si were highest in T_5.
- Significantly lowest nutrient uptake was observed in absolute control.
- Nutrient uptake had highly significant and positive correlation with available nutrients in soil.

Adopting a nutrient management strategy which is economically viable, ecologically sound and environment friendly would help to obtain higher productivity, maintaining soil health. Integrating soil test based nutrient recommendation along with vermicomposted rice straw at 5t ha^{-1} proved superior in augmenting soil fertility and crop productivity in the highly weathered, nutrient poor acidic lateritic soils under AEU 10. Improvement in soil physical properties and enhancement of total carbon emerged as the added advantages of applying rice straw and husk based biochar. However, long term studies may be essential with biochar to assess its extended effect and also for quantifying the amount of recalcitrant carbon supplied and sequestered in soil.

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ABSTRACT

NUTRIENT DYNAMICS AND CROP PRODUCTIVITY IN LOWLAND LATERITIC SOIL (AEU 10) UNDER RICE RESIDUE MANAGEMENT PRACTICES

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ABSTRACT OF THE THESIS

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ABSTRACT

The present investigation was undertaken at College of Agriculture Vellanikkara, Kerala Forest Research Institute Peechi, and Agricultural Research Station Mannuthy during 2017-2020. The experiment comprised of characterization of rice residues and their products for physical and chemical properties, an incubation experiment to study the kinetics of carbon mineralization, and a field experiment to evaluate the efficacy of rice residues and their products on lowland rice.

Straw and husk, the important residues produced during the cultivation and processing of rice, respectively was procured from farmer's field and further materials required for the research work *viz*., vermicomposted rice straw (VRS), vermicomposted rice husk (VRH), rice straw biochar (RSB), and rice husk biochar (RHB) were produced from the straw (RS) and husk (RH) using vermitechnology and pyrolysis.

Recovery from vermicomposting was more (74.38 % for VRS and 70.03 % for VRH) than when the residues were converted into biochar through pyrolysis (19.86 % for RSB and 38.00 % for RHB). Vermicomposting and pyrolysis reduced the bulk density of raw materials. Rice residues and their products were alkaline, with biochar exhibiting the highest level of alkalinity (9.24 for RSB and 9.20 for RHB). The electrical conductivity increased both by vermicomposting and pyrolysis. Straw was comparatively superior to the husk in respect of C, N, K, Ca, Mg, Fe, Mn, Cu, and Zn. However, husk was superior in P, S, B, Si, cellulose, and lignin. Vermicomposting helped to concentrate the nutrients *viz*., N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, B, and Si while reducing that of carbon, cellulose and lignin thereby narrowing down the C: N ratio. However, C: N ratio increased upon pyrolysis.

Surface morphology of rice residues and their products were studied using scanning electron microscope (SEM). The SEM micrographs of straw and husk exhibited a complex morphology with cell wall composition. SEM micrograph of VRS showed highly fragmented, disaggregated and porous structure which could not be visualised in VRH, may be because the technology of composting using earthworms was more suited to decomposing rice straw than its husk. The SEM analysis showed that the structure of biochar was porous, fragmented and particles gave a broken or distorted appearance thus resembling the plant structure. The structural chemistry of rice residues and their products were analysed using fourier transform infra red spectrometer (FT-IR). Each peak is characteristic of corresponding

functional group and it clearly explained the presence of C, H, O, N, and Si in the residues and products. Silicon, a major component in the chemical structure of rice material was illustrated by Si-O-Si and Si-H bond in FT-IR spectra. Vermicompost had significant level of nitrogen rich compounds and low level of aliphatic or aromatic carbon compounds compared to biochar, as confirmed by the FT-IR analysis. The FT-IR spectra of RSB and RHB revealed its aromatic and recalcitrant nature.

The incubation experiment was conducted for 110 days at 15, 25, 35 and 45 ºC to study the kinetics of carbon mineralization in lateritic soil over time, wherein the CO_2 evolution was determined at frequent intervals and the data were used for determination of carbon mineralization and mineralization kinetics. Lateritic soils (100g) collected from Agricultural Research Station Mannuthy, were treated with rice residues and their products (5t ha^{-1}), FYM (5 t ha^{-1}), and soil test based nutrient recommendation. An absolute control without the addition of organic/inorganic materials was also maintained. Dehydrogenase enzyme assay, enumeration of microbial population, and fractions of carbon were also undertaken at the end of incubation.

Results of incubation experiment revealed that the amount of CO_2–C mineralized during incubation increased with rise in temperature in all the treatments. The VRS treated soils registered higher mineralizable carbon at 15, 25, 35 and 45 ºC. The rate of decomposition reaction was highest in soils that are treated with VRS and FYM. The highest activation energy was found in RHB amended soil (12.79 kJ mol^{-1}) followed by RSB treated soil (12.71 kJ mol^{-1}). Q_{10} values represent the temperature dependency of the reaction. The results showed that all treatments had Q_{10} values less than one.

After incubation experiment, dehydrogenase activity as well as microbial population was found to decrease at 45 ºC compared to the values at lower temperature. Comparatively, higher dehydrogenase activity and microbial population was registered in soils treated with VRS. The soils treated with VRS exhibited highest water soluble carbon (WSC), hot water extractable carbon (HWEC), microbial biomass carbon (MBC), and permanganate oxidizable carbon (POXC). However, biochar amended soils (RHB and RSB) registered higher value of total carbon.

A field experiment was carried out to evaluate the efficacy of rice residues and their products in lowland with rice variety Uma as the test crop. The experiment consisted of nine treatments with three replications *viz*., absolute control (T_1), Adhoc KAU organic POP (T_2), and treatments T_3 to T_9 comprised of soil test based nutrient recommendation along with FYM (T_3), VRH (T_4), VRS (T_5), RHB (T_6), RSB (T_7), RH (T_8), and RS (T_9) at 5t ha^{-1}. At weekly intervals Eh and pH were monitored. The soil and plant samples were collected at different stages of rice to analyse the effect of treatments on soil physical and chemical properties, fractions of nutrients in soil, nutrient content in plant, soil enzyme activity, and growth, yield and yield attributes of rice.

Results of field experiment revealed that the application of residues and its products had a profound influence in lowering redox potential. The alkaline nature of rice residues and their products resulted in higher pH of experimental soil. Physical properties of post-harvest soil was improved by the application of T_6 and T_7 (soil test based nutrient recommendation + RHB and RSB).

The application of T_5 (soil test based nutrient recommendation + VRS at 5 t ha^{-1}) was superior in increasing the nutrient status of post-harvest soil *viz*., C, N, P, Ca, Mg, S, Fe, Mn, Zn, and Si. While, K content was superior in T_7 (soil test based nutrient recommendation + RSB at 5 t ha^{-1}). Soils receiving combined application of soil test based nutrient recommendation and VRS at 5 t ha^{-1} (T_5) recorded the highest WSC, HWEC, MBC, POXC, inorganic-N and P fractions, fractions of Ca and Mg at all the stages of crop. However, total-C, total hydrolysable-N, organic-P, and Si fractions were higher in biochar amended plots. Soil receiving joint application of soil test based nutrient recommendation +RSB at 5 t ha^{-1} (T_7) was statistically superior in fractions of K at all stages.

Enzyme activity (dehydrogenase, urease, and acid phosphatase) was found to be highest in T_5 (soil test based nutrient recommendation + VRS at 5 t ha^{-1}), and it followed an increasing trend upto panicle initiation and thereafter it decreased in all treatments. The uptake of N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B and Si were also highest in T_5. With respect to the growth, yield and yield attributes of rice, application of soil test based nutrient recommendation + VRS at 5 t ha^{-1} (T_5) had superior effect.

To conclude, the study has brought out the tremendous potential of rice straw and husk based biochar in improving soil physical properties and in elevating the total carbon content. However, the integration of soil test based nutrient recommendation with vermicomposted rice straw at 5t ha^{-1} (T_5) proved outstanding in augmenting soil fertility and crop productivity in the highly weathered, nutrient poor acidic lateritic soils.